15

Testing a system

Does it work? This is the first question that occurs to us once we have carried out any work on an optic fiber system. There are several different tests we can conduct. We will start with the simplest.

Remember to take precautions to avoid accidental viewing of 'live' fibers

---

Visible light continuity test

For short lengths of multimode cable up to about 100 meters any source of white light can be used. The end of the fiber can be held against a flashlight or an electric light bulb or even sunlight if it is available. The range obviously depends on the brightness of the light source and the losses on the fiber, so an absolute limit is impossible to quote. This method is commonly used to test short connecting cables called *patchcords*, *patch cables* or *jumper cables*. These are short lengths of easily replaceable cable, typically 5–20 meters in length, used to connect between enclosures and instruments. At the far end, our eyes can detect the light more easily if we switch it on and off rather than just leaving it permanently on. The range can be extended up to a kilometer using an ultrabright red light LED. This test will tell you little more however than if the fiber is badly broken or not.

Light source and power meter

The previous methods have provided a quick and easy go/no go test over a limited distance. The benefit of using a light source and power meter is that they are able to measure the actual power loss of the fiber system.

Mode stripper or mode filter

When we shine light down an optic fiber, the light source is wider than the core of the fiber and much of the light will enter the cladding. Propagation of the light is shown in Figure 4.29. This additional light will give a false indication when we come to measure the losses on a fiber, as the light escapes from the cladding surface (see Figure 4.30).

This light, or extra modes, will escape during the first 1 km (3300 ft) although half this distance is normally enough to reduce the power to a negligible value. An alternative to a long length of fiber is to use a mode stripper, also called a mode filter. This is a device that makes the light escape much faster than in a normal fiber so that we can lose all the unwanted modes in about 300 mm (12 in) of fiber.

This amazing trick is achieved by tightly coiling the fiber to create bending losses. As the fiber is coiled through a diameter of about 20 mm (0.8 in), the light traveling along the cladding is removed without seriously interfering with the core transmission.

Mode strippers are bought ready-made with connectors on each end (Figure 15.1).

Figure 15.1

Mode filter

Buy it or wind your own

Coil diameter
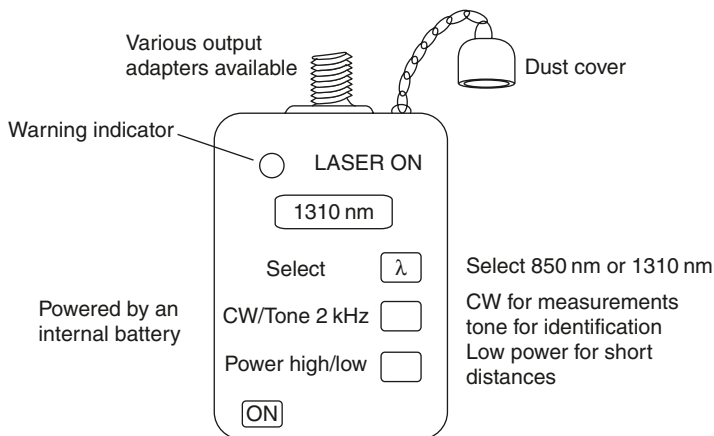20 mm (0.8 in)
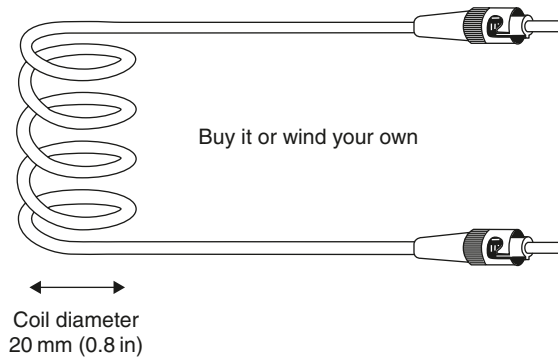
Light source – Figure 15.2

A light source is a hand-held instrument able to provide a light output within one or more of the standard windows: visible, 850 nm, 1300 nm and 1550 nm using an LED or laser light source. They often provide outputs at more than one of the wavelengths, as installation contracts generally require measurements to be taken at two different wavelengths and of course the popular choice being 850 nm and 1300 nm.

For reliable results, the power output of the light must be very stable over the period of the test, typically within 0.1 dB over 1 hour. The output can be switched between a test tone of 2 kHz or 270 Hz or 10 kHz and a continuous output called *CW* (*continuous wave*). The choice of test tones allows easy identification of fibers under test.
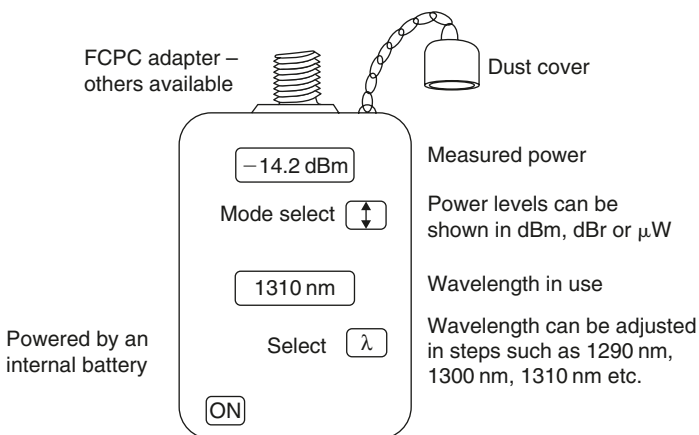
Power meter

At first glance, these look very similar to the light sources. Compare Figures 15.2 and 15.3. They are often sold as matching pairs though there is nothing to prevent any light meter and power meter being used together provided they are compatible.

Figure 15.2

A light source

Various output adapters available

Dust cover

Warning indicator

LASER ON

1310 nm

Select   λ   Select 850 nm or 1310 nm

Powered by an internal battery

CW/Tone 2 kHz   CW for measurements tone for identification

Power high/low   Low power for short distances

ON

Figure 15.3

Power meter

FCPC adapter – others available

Dust cover

−14.2 dBm   Measured power

Mode select   Power levels can be shown in dBm, dBr or μW

1310 nm   Wavelength in use

Powered by an internal battery

Select   λ   Wavelength can be adjusted in steps such as 1290 nm, 1300 nm, 1310 nm etc.

ON

The wavelength is adjustable over the three windows and some offer a facility to step up and down by small increments. This allows the fiber characteristics to be quoted at any required wavelength. It is a 'nice to have' rather than an essential feature.

The power levels can be indicated in μW or in decibels as dBm, relative to one milliwatt or as dBr, relative to a previously noted value.

They are available with internal memories to store the day's work and a printer for hard copies.

Calibration (or traceability)

If the light source and power meter are to be used to check an installation or repair on a commercial basis, the customer will need assurance that your instruments are telling the truth. The proof of this is provided by a calibration certificate for each instrument which must be renewed at intervals, usually annually. The calibration must be carried out by an authorized company whose instruments themselves are calibrated against the appropriate national standards. In this way we can trace the accuracy back to its source.

An example measurement

To measure the losses in a typical link as shown in Figure 15.4, we start by selecting a patchcord about 20 m in length. If possible, it should be constructed from fiber of the same type and fitted with identical connectors to those used in the link to be tested. In cases where this is not possible, reduced accuracy in the final result will have to be tolerated. Keep a record of the patchcord and the instruments used so that the measurement could be repeated if a doubt arises at a later date.

Figure 15.4

The optic fiber to be tested
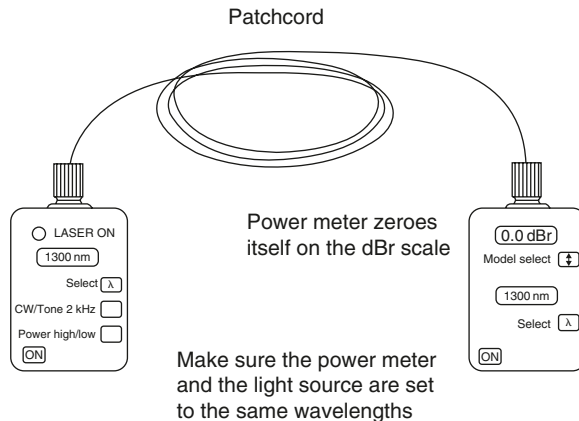

Optic fiber link

Transmitter

Receiver

Step 1   Setting up the light source and power meter

Connect the meters together using the patchcord as shown in Figure 15.5. Switch them on. Select the required wavelength and, on the power meter, switch to dBr mode.

Figure 15.5

Measuring power from the light source

Patchcord

Power meter zeroes itself on the dBr scale

Make sure the power meter and the light source are set to the same wavelengths

Wait until the readings have stabilized. At this stage, the power meter will indicate the incoming power level in dBm. Set the power meter to dBr and it will accept the incoming light level as the reference level. The reading will now change to 0 dBr.
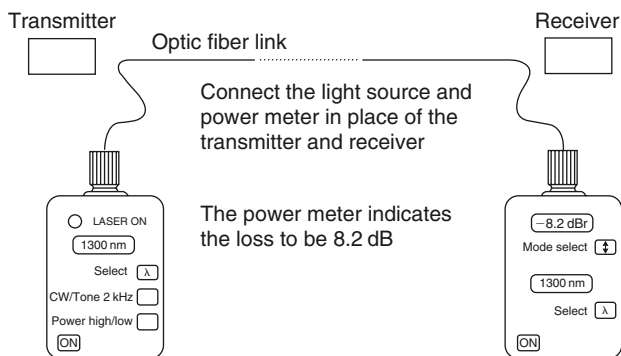
Both the light source and the power meter must remain switched on now until all the measurements have been completed. This is to give the light source a good chance of maintaining a constant light level since the internal temperature and battery voltage will (hopefully) remain stable. The power meter needs to remain on in order to remember the level set as 0 dBr.

Disconnect the patchcord.

Step 2   Connecting them to the system – Figure 15.6

Disconnect the fiber to be tested at the transmitter and plug in the light source. Connect the power meter to the far end. The power meter will immediately show

Figure 15.6

Measuring the
loss in the
optic fiber link

Transmitter

Optic fiber link

Receiver

Connect the light source and
power meter in place of the
transmitter and receiver

○ LASER ON

1300 nm

Select λ

CW/Tone 2 kHz

Power high/low

ON

The power meter indicates
the loss to be 8.2 dB

−8.2 dBr

Mode select

1300 nm

Select λ

ON

a new figure such as −8.2 dBr. This is the loss over the system. We have actually
assumed the patchcord loss (about 0.05 dB) to be small enough to be ignored.

No dBr mode?

Some very basic power meters do not have a dBr facility. Apart from inflicting
some calculations on the user, the results will be the same.

Step 1   The power out from the light source

Using such a meter in the above system, we would have read the light source
power out in dBm – let's assume this to be −10 dBm.

Step 2   The power out from the link

Leaving the meters switched on, connect them to the optic fiber link. The power
meter would now indicate −18.2 dBm.

Step 3   The extra bit

The loss in the optic fiber link is the difference between the two measurements,
$(−10.0) − (−18.2) = 8.2$ dB as in the previous case.

Limitations of the light source and power meter method

Assume an optic fiber link has become unreliable. Meters would give an accu-
rate enough result for the overall loss of a system which would confirm that
additional losses have occurred. They are, however, unable to indicate which
part of the system is responsible for the additional loss.

Power meter/light source combinations are the quickest and cheapest method
for acceptance testing of a short-haul datacoms link because they give a clear
unambiguous reading of the light loss between A and B; the user can decide if
that result is acceptable or not. If there is a fault the power meter/light source
will indicate this, but it can't tell what or where that fault is. This is where an
optical time domain reflectometer, or *OTDR*, comes in.

The optical time domain reflectometer (OTDR)

This instrument is connected to one end of any fiber optic system up to 250 km in
length. Within a few seconds, we are able to measure the overall loss, or the loss

of any part of a system, the overall length of the fiber and the distance between any points of interest.

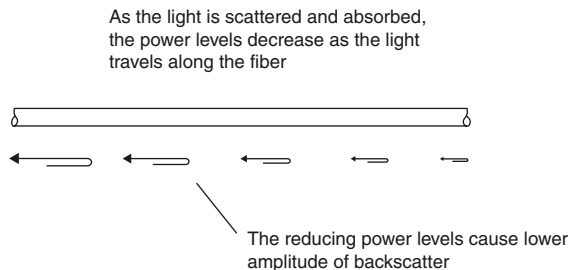## A use for Rayleigh scatter – Figure 15.7

As light travels along the fiber, a small proportion of it is lost by Rayleigh scattering. As the light is scattered in all directions, some of it just happens to return back along the fiber towards the light source. This returned light is called *backscatter*.

Figure 15.7

Backscatter

Rayleigh scatter includes some light returned towards the light source

Light source

Scattering discontinuities
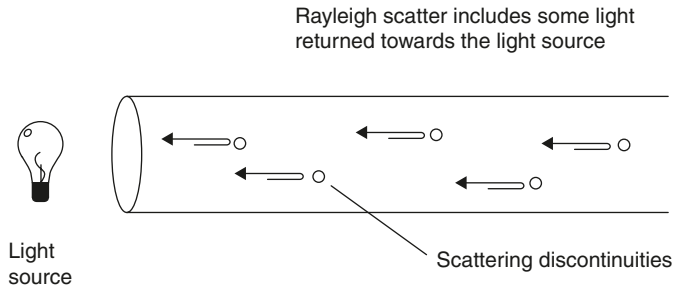
The backscatter power is a fixed proportion of the incoming power and as the losses take their toll on the incoming power, the returned power also diminishes as shown in Figure 15.8.

Figure 15.8

The backscatter becomes weaker

As the light is scattered and absorbed, the power levels decrease as the light travels along the fiber

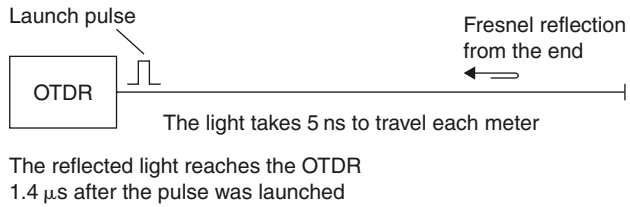The reducing power levels cause lower amplitude of backscatter

The OTDR can continuously measure the returned power level and hence deduce the losses encountered on the fiber. Any additional losses such as connectors and fusion splices have the effect of suddenly reducing the transmitted power on the fiber and hence causing a corresponding change in backscatter power. The position and the degree of the losses can be ascertained.

Measuring distances – Figure 15.9

The OTDR uses a system rather like a radar set. It sends out a pulse of light and 'listens' for echoes from the fiber.

If it knows the speed of the light and can measure the time taken for the light to travel along the fiber, it is an easy job to calculate the length of the fiber.

Figure 15.9
**How long is
the fiber?**

Launch pulse

Fresnel reflection
from the end

OTDR

The light takes 5 ns to travel each meter

The reflected light reaches the OTDR
1.4 μs after the pulse was launched

To find the speed of the light

Assuming the refractive index of the core is 1.5, the infrared light travels in the
glass at a speed of:

$$\frac{\text{speed of light in free space}}{\text{refractive index of the core}} = \frac{3 \times 10^8}{1.5} = 2 \times 10^8 \, \text{ms}^{-1}$$

This means that it will take:

$$\frac{1}{2 \times 10^8} \, \text{s} \quad \text{or} \quad 5 \, \text{ns to travel a distance of one meter}$$

This is a useful figure to remember, 5 nanoseconds per meter (5 nsm^{-1}).

If the OTDR measures a time delay of 1.4 μs, then the distance traveled by the
light is:

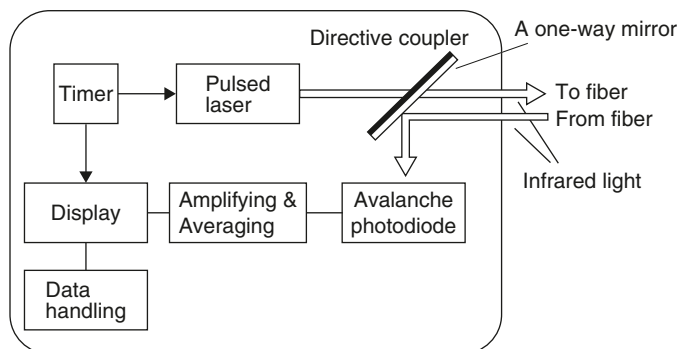$$\frac{1.4 \times 10^{-6}}{5 \times 10^{-9}} = 280 \, \text{m}$$

The 280 meters is the total distance traveled by the light and is the 'there and
back' distance. The length of the fiber is therefore only 140 m. This adjustment is
performed automatically by the OTDR – it just displays the final result of 140 m.

Inside the OTDR – Figure 15.10

Timer

The timer produces a voltage pulse which is used to start the timing process in
the display at the same moment as the laser is activated.

Figure 15.10
**A block
diagram of
an OTDR**

Directive coupler

A one-way mirror

Timer

Pulsed
laser

To fiber
From fiber

Display

Amplifying &
Averaging

Avalanche
photodiode

Infrared light

Data
handling

Pulsed laser

The laser is switched on for a brief moment. The 'on' time being between 1 ns and 10 μs. We will look at the significance of the choice of 'on' time or pulsewidth in a moment or two. The wavelength of the laser can be switched to suit the system to be investigated.

Directive coupler

The directive coupler allows the laser light to pass straight through into the fiber under test. The backscatter from the whole length of the fiber approaches the directive coupler from the opposite direction. In this case the mirror surface reflects the light into the avalanche photodiode (an APD). The light has now been converted into an electrical signal.

Amplifying & averaging

The electrical signal from the APD is very weak and requires amplification before it can be displayed. The averaging feature is quite interesting and we will look at it separately towards the end of this chapter.
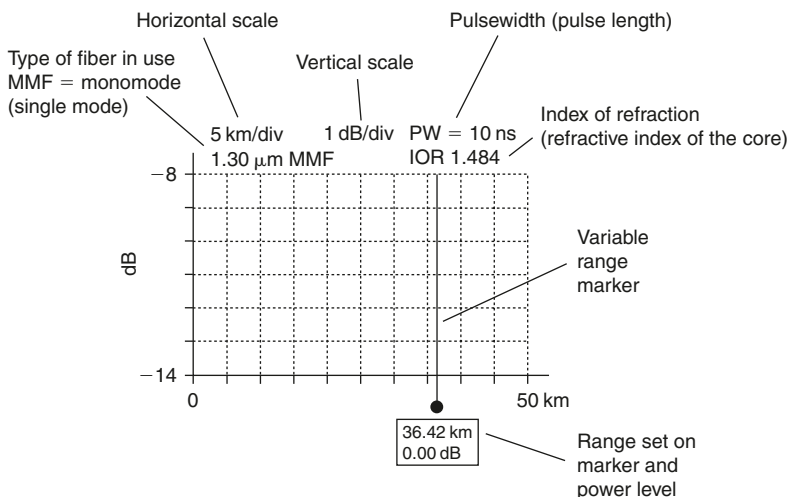
Display

The amplified signals are passed on to the display. The display is either a cathode ray tube (CRT) like an oscilloscope or a computer monitor, or a liquid crystal as in calculators and laptop computers. They display the returned signals on a simple XY plot with the range across the bottom and the power level in decibels up the side.

Figure 15.11 shows a typical display. The current settings are shown immediately over the grid. They can be modified to suit the measurements being undertaken. The range scale displayed shows a 50 km length of fiber. In this case it is from 0 to 50 km but it could be any other 50 km slice, for example, from 20 km to 70 km.

Figure 15.11

An OTDR display – no signal

Horizontal scale

Pulsewidth (pulse length)

Type of fiber in use MMF = monomode (single mode)

Vertical scale

Index of refraction (refractive index of the core)

5 km/div   1 dB/div   PW = 10 ns
1.30 μm MMF   IOR 1.484

−8

dB

−14

0

50 km

Variable range marker

36.42 km
0.00 dB

Range set on marker and power level

163

It can also be expanded to give a detailed view of a shorter length of fiber such as 0–5 m, or 25–30 m.

The ranges can be read from the horizontal scale, but for more precision a variable range marker is used. This is a movable line which can be switched on and positioned anywhere on the trace. Its range is shown on the screen together with the power level of the received signal at that point. To find the length of the fiber, the marker is simply positioned at the end of the fiber and the distance is read off the screen. It is usual to provide up to five markers so that several points can be measured simultaneously.

Data handling

An internal memory or a floppy disk drive can store the data for later analysis. The output is also available via an RS232 link for downloading to a computer. In addition, many OTDRs have an onboard printer to provide hard copies of the information on the screen. This provides useful 'before and after' images for fault repair as well as a record of the initial installation.

A simple measurement

If we were to connect a length of fiber, say 300 m, to the OTDR the result would look as shown in Figure 15.12.

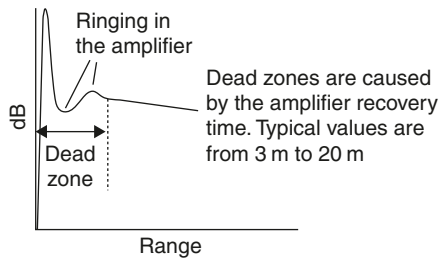**Figure 15.12**
A simple fiber measurement
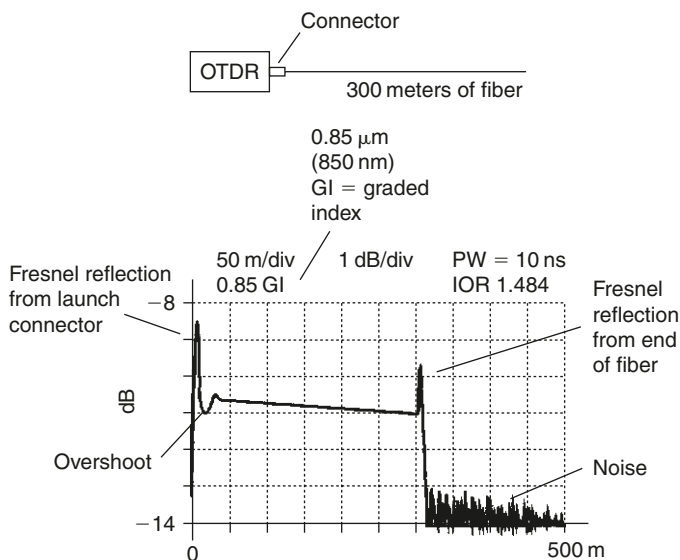
Whenever the light passes through a cleaved end of a piece of fiber, a Fresnel reflection occurs. This is seen at the far end of the fiber and also at the launch connector. Indeed, it is quite usual to obtain a Fresnel reflection from the end of the fiber without actually cleaving it. Just breaking the fiber is usually enough. The Fresnel at the launch connector occurs at the front panel of the OTDR and, since the laser power

is high at this point, the reflection is also high. The result of this is a relatively high pulse of energy passing through the receiver amplifier. The amplifier output voltage swings above and below the real level, in an effect called *ringing*. This is a normal amplifier response to a sudden change of input level. The receiver takes a few nano-seconds to recover from this sudden change of signal level.

Dead zones

The Fresnel reflection and the subsequent amplifier recovery time result in a short period during which the amplifier cannot respond to any further input signals. This period of time is called a *dead zone*. It occurs to some extent whenever a sudden change of signal amplitude occurs. The one at the start of the fiber where the signal is being launched is called the *launch dead zone* and others are called *event dead zones* or just *dead zones* (see Figures 15.13 and 15.21).
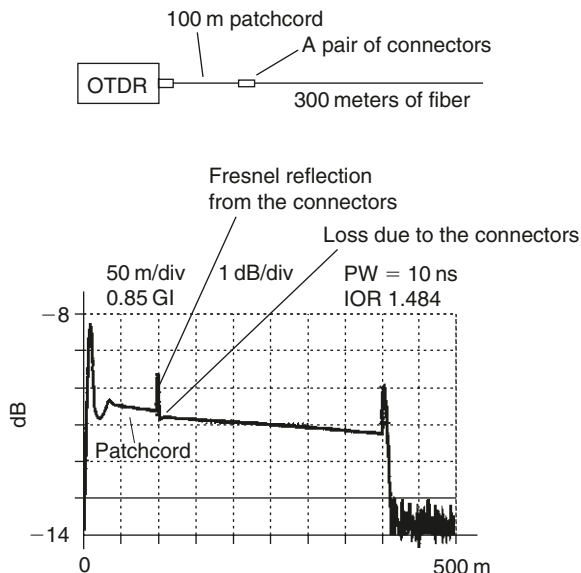
Figure 15.13

Dead zone

(see also

Figure 15.21)

Overcoming the launch dead zone – Figure 15.14

As the launch dead zone occupies a distance of up to 20 meters or so, this means that given the job of checking a 300 m fiber, we may only be able to check 280 m of it. The customer would not be delighted.

Figure 15.14

A patchcord

overcomes

dead zone

problems

To overcome this problem, we add our own patchcord at the beginning of the system. If we make this patchcord about 100 m in length, we can guarantee that all launch dead zone problems have finished before the customer's fiber is reached.

The patchcord is joined to the main system by a connector which will show up on the OTDR readout as a small Fresnel reflection and a power loss. The power loss is indicated by the sudden drop in the power level on the OTDR trace.

## Fiber length and attenuation

The end of the fiber appears to be at 400 m on the horizontal scale but we must deduct 100 m to account for our patchcord. This gives an actual length of 300 m for the fiber being tested.

Immediately after the patchcord Fresnel reflection, the power level shown on the vertical scale is about -10.8 dB and at the end of the 300 m run, the power has fallen to about -11.3 dB. A reduction in power level of 0.5 dB in 300 meters indicates a fiber attenuation of:

$$\frac{\text{attenuation}}{\text{length in kilometers}} = \frac{0.5}{0.3} = 1.66 \text{ dB km}^{-1}$$

Most OTDRs provide a loss measuring system using two markers. The two markers are switched on and positioned on a length of fiber which does not include any other events, like connectors or whatever as shown in Figure 15.15.

Figure 15.15
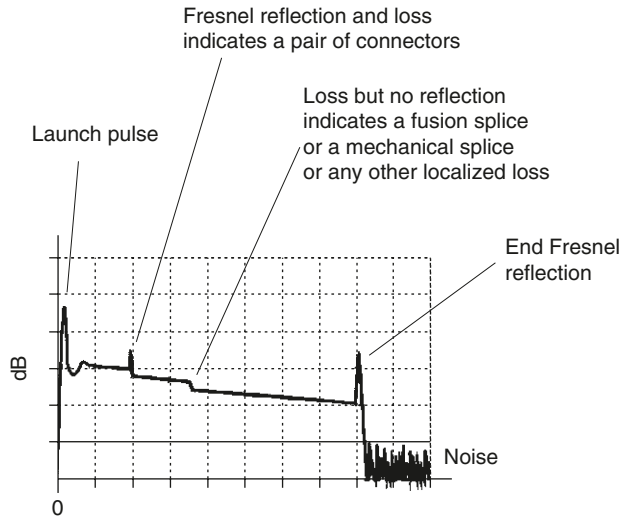Using two
markers for loss
measurement
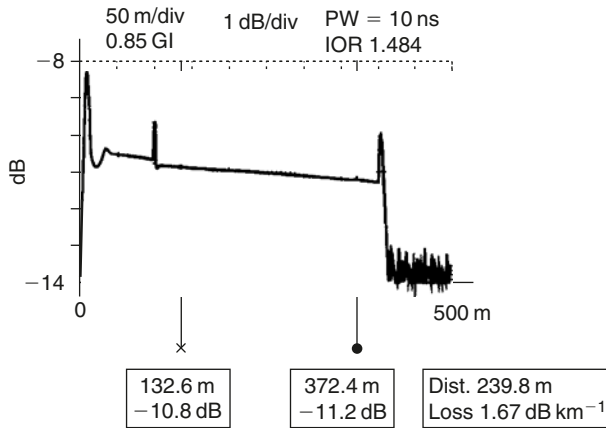
The OTDR then reads the difference in power level at the two positions and the distance between them, performs the above calculation for us and displays the loss per kilometer for the fiber. This provides a more accurate result than trying to read off the decibel and range values from the scales on the display and having to do our own calculations.

An OTDR display of a typical system

The OTDR can 'see' Fresnel reflections and losses. With this information, we can deduce the appearance of various events on an OTDR trace as seen in Figure 15.16.

Figure 15.16

A typical

OTDR trace

Fresnel reflection and loss
indicates a pair of connectors

Loss but no reflection
indicates a fusion splice
or a mechanical splice
or any other localized loss

Launch pulse

End Fresnel
reflection

dB

Noise

0

Connectors

A pair of connectors will give rise to a power loss and also a Fresnel reflection due to the polished end of the fiber.

Fusion splice

Fusion splices do not cause any Fresnel reflections as the cleaved ends of the fiber are now fused into a single piece of fiber. They do, however, show a loss of power. A good quality fusion splice will actually be difficult to spot owing to the low losses. Any sign of a Fresnel reflection is a sure sign of a very poor fusion splice.

Mechanical splice

Mechanical splices appear similar to a poor quality fusion splice. The fibers do have cleaved ends, of course, but the Fresnel reflection is avoided by the use of index matching gel within the splice. The losses to be expected are similar to the least acceptable fusion splices.
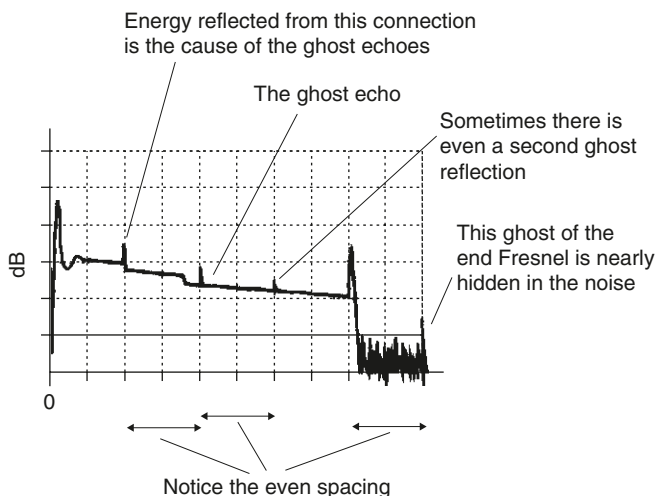
Bend loss

This is simply a loss of power in the area of the bend. If the loss is very localized, the result is indistinguishable from a fusion or mechanical splice.

Ghost echoes (false reflections)

In Figure 15.17, some of the launched energy is reflected back from the connectors at the end of the patchcord at a range of 100 m. This light returns and strikes the polished face of the launch fiber on the OTDR front panel. Some of this energy is again reflected to be relaunched along the fiber and will cause another indication from the end of the patchcord, giving a false, or *ghost*, Fresnel reflection at a range of 200 m and a false *end* to the fiber at 500 m.

167

Figure 15.17

Ghosts

Energy reflected from this connection
is the cause of the ghost echoes

The ghost echo

Sometimes there is
even a second ghost
reflection

This ghost of the
end Fresnel is nearly
hidden in the noise

dB

0

Notice the even spacing

As there is a polished end at both ends of the patchcord, it is theoretically pos-
sible for the light to bounce to and fro along this length of fiber giving rise to a
whole series of ghost reflections. In Figure 15.17 a second reflection is shown at
a range of 300 m.

It is very rare for any further reflections to be seen. We have seen earlier that the
maximum amplitude of the Fresnel reflection is 4% of the incoming signal, and
is usually much less. Looking at the calculations for a moment, even assuming
the worst reflection, the returned energy is 4% or 0.04 of the launched energy.
The relaunched energy, as a result of another reflection is 4% of the 4% or
$0.04^2 = 0.0016 \times$ input energy. This shows that we need a lot of input energy
to cause a ghost reflection. A second ghost would require another two reflec-
tions giving rise to a signal of only 0.000 002 56 of the launched energy.
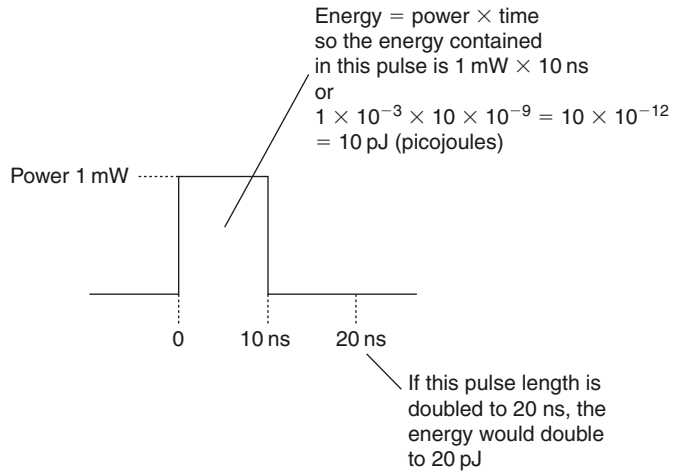Subsequent reflections die out very quickly as we could imagine.

Ghost reflections can be recognized by their even spacing. If we have a reflec-
tion at 387 m and another at 774 m then we have either a strange coincidence
or a ghost. Ghost reflections have a Fresnel reflection but do not show any loss.
The loss signal is actually of too small an energy level to be seen on the display.
If a reflection shows up after the end of the fiber, it has got to be a ghost.

Effects of changing the pulsewidth

The maximum range that can be measured is determined by the energy con-
tained within the pulse of laser light. The light has to be able to travel the full
length of the fiber, be reflected, and return to the OTDR and still be of larger
amplitude than the background noise. Now, the energy contained in the pulse is
proportional to the length of the pulse and so to obtain the greatest range the
longest possible pulsewidth should be used, as illustrated in Figure 15.18.

Figure 15.18
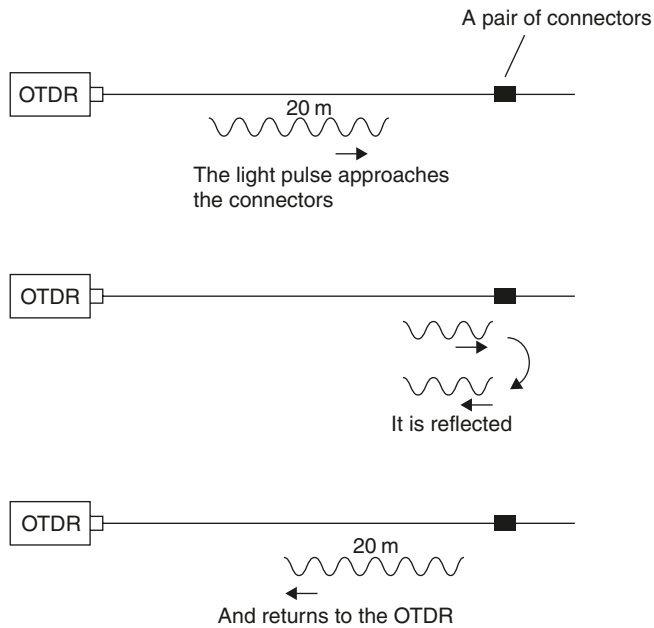
A longer pulse

contains more

energy

Energy = power × time
so the energy contained
in this pulse is 1 mW × 10 ns
or
$1 \times 10^{-3} \times 10 \times 10^{-9} = 10 \times 10^{-12}$
$= 10 \, \text{pJ (picojoules)}$

Power 1 mW ········

0   10 ns   20 ns

If this pulse length is
doubled to 20 ns, the
energy would double
to 20 pJ

This cannot be the whole story, as OTDRs offer a wide range of pulsewidths.

We have seen that light covers a distance of one meter every five nanoseconds
so a pulsewidth of 100 ns would extend for a distance of 20 meters along the
fiber (Figure 15.19). When the light reaches an event, such as a connector, there

Figure 15.19

A 100 μs

pulse causes a

20 m reflection

A pair of connectors

OTDR

20 m

The light pulse approaches
the connectors

OTDR

It is reflected

OTDR

20 m

And returns to the OTDR

is a reflection and a sudden fall in power level. The reflection occurs over the
whole of the 20 m of the outgoing pulse. Returning to the OTDR is therefore a
20 m reflection. Each event on the fiber system will also cause a 20 m pulse to
be reflected back towards the OTDR.

169

Now imagine two such events separated by a distance of 10 m or less as in Figure 15.20. The two reflections will overlap and join up on the return path to

Figure 15.20

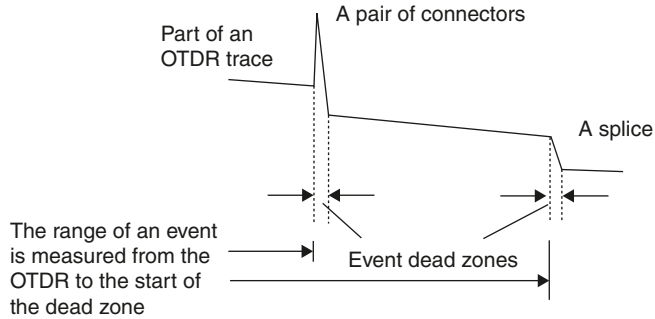Pulse length determines the range discrimination
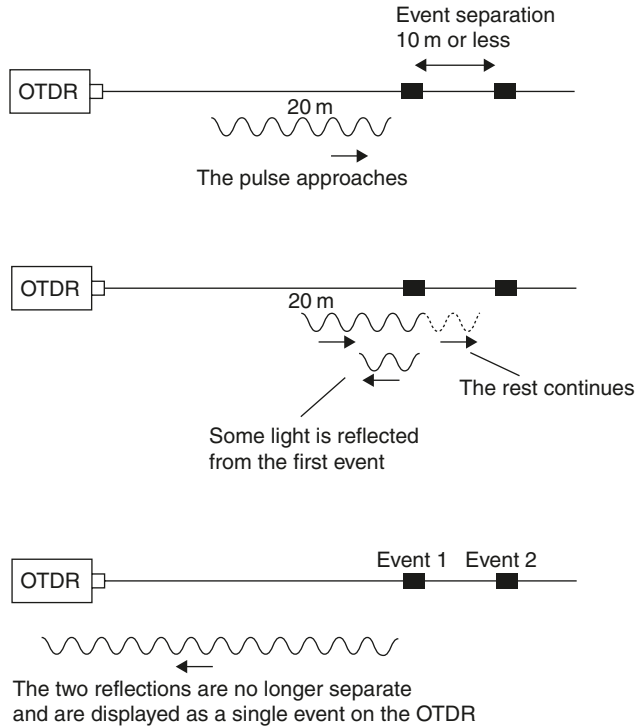
the OTDR. The OTDR will simply receive a single burst of light and will be quite unable to detect that two different events have occurred. The losses will add together, so two fusion splices, for example, each with a loss of 0.2 dB will be shown as a single splice with a loss of 0.4 dB. The minimum distance separating two events that can be displayed separately is called the range discrimination of the OTDR.

The shortest pulsewidth on an OTDR may well be in the order of 10 ns so at a rate of 5 nsm^{-1} this will provide a pulse length in the fiber of 2 m. The range discrimination is half this figure so that two events separated by a distance greater than one meter can be displayed as separate events. At the other end of the scale, a maximum pulsewidth of 10 μs would result in a range discrimination of one kilometer.

Another effect of changing the pulsewidth is on dead zones. Increasing the energy in the pulse will cause a larger Fresnel reflection. This, in turn, means that the amplifier will take longer to recover and hence the event dead zones will become longer as shown in Figure 15.21.

Figure 15.21

Event dead

zones and

distances

A pair of connectors

Part of an
OTDR trace

A splice

The range of an event
is measured from the
OTDR to the start of
the dead zone

Event dead zones

Which pulsewidth to use?

Most OTDRs give a choice of at least five different pulse lengths from which to select.

Low pulsewidths mean good separation of events but the pulse has a low energy content so the maximum range is very poor. A pulsewidth of 10 ns may well provide a maximum range of only a kilometer with a range discrimination of one meter.

The wider the pulse, the longer the range but the worse the range discrimination. A 1 μs pulsewidth will have a range of 40 km but cannot separate events closer together than 100 m.

As a general guide, use the shortest pulse that will provide the required range.

Averaging

The instantaneous value of the backscatter returning from the fiber is very weak and contains a high noise level which tends to mask the return signal.

As the noise is random, its amplitude should average out to zero over a period of time. This is the idea behind the averaging circuit. The incoming signals are stored and averaged before being displayed. The larger the number of signals averaged, the cleaner will be the final result but the slower will be the response to any changes that occur during the test. The mathematical process used to perform the effect is called *least squares averaging* or LSA.
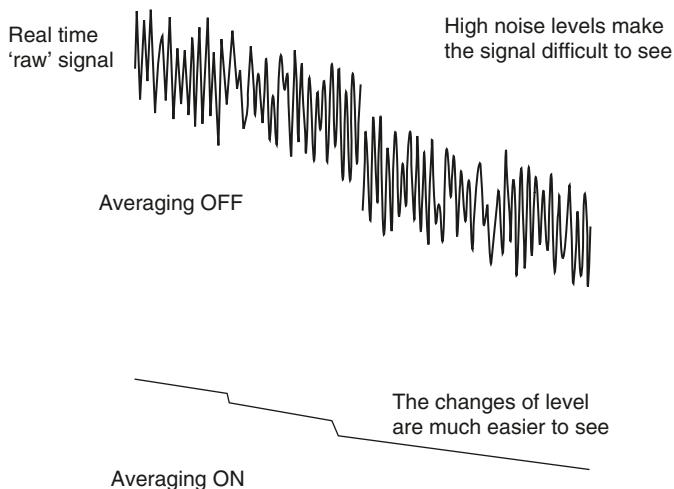
Figure 15.22 demonstrates the enormous benefit of employing averaging to reduce the noise effect. Occasionally it is useful to switch the averaging off to see a *real time* signal from the fiber to see the effects of making adjustments to connectors, etc. This is an easy way to optimize connectors, mechanical splices, bends etc. simply fiddle with it and watch the OTDR screen.

Dynamic range

When a close range reflection, such as the launch Fresnel occurs, the reflected energy must not be too high otherwise it could damage the OTDR receiving circuit.

171

Figure 15.22

The benefits of

averaging

Real time 'raw' signal

High noise levels make the signal difficult to see

Averaging OFF

The changes of level are much easier to see

Averaging ON

The power levels decrease as the light travels along the fiber and eventually the reflections are similar in level to that of the noise and can no longer be used.

The difference between the highest safe value of input power and the minimum detectable power is called the dynamic range of the OTDR and, along with the pulsewidth and the fiber losses, determines the useful range of the equipment. If an OTDR was quoted as having a dynamic range of 36 dB, it could measure an 18 km run of fiber with a loss of 2 dB km^{-1}, or alternatively a 72 km length of fiber having a loss of 0.5 dB km^{-1}, or any other combination that multiplies out to 36 dB.

Fault locator

These devices are used to locate faults quickly and easily rather than provide a detailed analysis of a system, and are therefore more likely to be met in a repair environment than at a new installation.

There are two types. The first is similar to the simple light source test.

This device extends the test range of a simple light source up to 5 km using a laser operating at 670 nm which is visible red light. It also provides a 2 kHz test tone which can be picked up by live fiber detectors and provides easy identification of the fiber under test.

If the continuity test fails, it can sometimes show us where the break has occurred. At the position of the break, the light is scattered. Using a powerful visible light source the fiber glows red from the scattered light. This assumes, of course, that the red light is able to penetrate the outer covering of the fiber.

The other device is very similar in principle to the OTDR. It is hand held and operated by internal batteries. It transmits an infrared light pulse along the fiber and 'listens out' for any sudden loss exceeding 0.25 dB, 0.5 dB or whatever value you have selected on the front panel control, all lesser events being ignored.

It doesn't actually provide us with a full OTDR type display but, instead, the result is shown on a liquid crystal display as a simple list of ranges at which losses exceed

the selected magnitude occur, together with the total length of the fiber. By comparing this information with the expected values, any discrepancy can be seen and any serious fault is located in seconds.

Quiz time 15

In each case, choose the best option.

1   For contract purposes, test equipment should:

(a) have a valid certificate of calibration

(b) be left switched on at all times

(c) be powered by internal batteries

(d) be manufactured by the same company as produced the fiber

2   Light sources often include a tone output. This enables:

(a) the length of the fiber to be calculated

(b) our eyes to see the infrared light more easily

(c) longer fibers to be tested
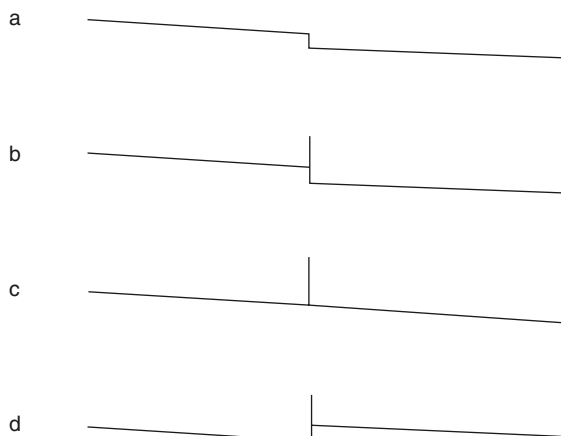
(d) easy identification of the fiber being tested

3   For detailed examination of a very short length of optic fiber cable, the OTDR should use the:

(a) shortest possible wavelength

(b) shortest possible pulsewidth

(c) longest available pulsewidth

(d) highest available power

4   Figure 15.23 shows a ghost reflection on an OTDR in option:

Figure 15.23
Question 4

a

b

c

d

(a)

(b)

(c)

(d)

---

5   The averaging facility of an OTDR can be switched off:

(a) to provide a real time response

(b) to remove noise and clean up the display of information

(c) to allow the peak power to be used

(d) if simultaneous measurements on more than one fiber system are
required

16

System design – or, will it work?

In designing a system, there are many factors to take into account. In this chapter we are looking at just two. We aim to satisfy ourselves that the transmitter is powerful enough for the light to reach the far end of the fiber and that the bandwidth is sufficient to enable the system to carry data at a high enough rate.

Optical power budget or loss budget or flux budget

If the signal is too weak when it reaches the far end of the system the data will be difficult to separate from the background noise. This will cause the number of errors in the received data bits to increase. If an error occurs once in every thousand million bits it would be said to have a *bit error rate* (BER) of 10^{-9} and is the usual lower limit of acceptability.

Limitations on the received power

1   The received power must be high enough to keep the BER to a low value.
2   The received power must be low enough to avoid damage to the receiver.

Limitations on the transmitted power

On cost and safety grounds it is good to keep the transmitter power to the minimum acceptable value.
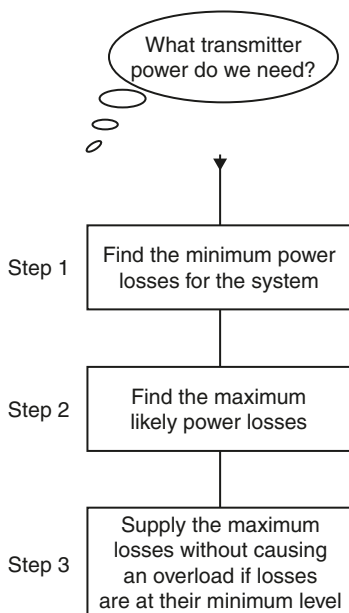
A problem

Having decided on the receiver and the system, what transmitter power would be needed?

Method of solving

This applies equally well to multimode, single mode silica fibers and to plastic fibers. The method is summarized in Figure 16.1.

Figure 16.1

How much

power do we

need?

Step 1

Find the minimum power losses due to the:

    1   fiber
    2   connectors
    3   and the splices.

These figures are obtained from the manufacturer either within the catalog or by contacting them.

Step 2

Find the maximum likely losses. This will include the:

    1   Minimum losses calculated above.
    2   Aging losses. Many components of a system deteriorate during their lifetime and it is important to know how much to allow for this, otherwise the system will crash at some future date. The aging loss is slight in fibers but the transmitter and the connectors, mechanical splices, couplers, etc. will need to be investigated. Again, the manufacturers will supply the data.

3   Repairs. This is a matter of judgment depending on the environment and stress to which the fiber will be subjected. It is clearly of little use to design a system that, although it works when first switched on, has so little spare power capacity that the extra loss incurred by a simple repair would be enough to make it fall over. A battlefield system would need more repair allowance than an installation in a building. This stage is really a guess based on experience and advice.

4   Spare. Keep a little extra in reserve – just in case. About 3 dB is a usual amount.

Step 3

Select a transmitter light source with enough power to enable the system to operate under the worst-case conditions with the maximum losses considered above. Then check to see if it would damage the receiver in the conditions of minimum loss. If necessary, an attenuator could be added with a view to removing it at a later date should repairs become necessary.
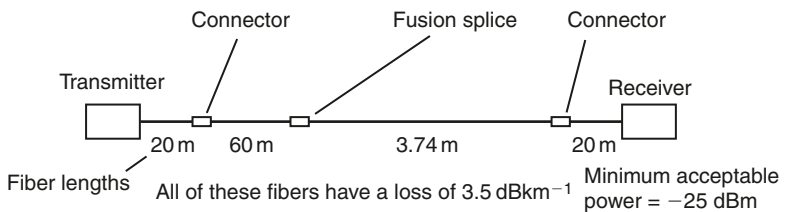
A worked example

As some of the values used are actually guesses (or informed estimates), it is to be expected that another person will achieve slightly different results.

Calculate the minimum transmitter power necessary in the system shown in Figure 16.2.

Figure 16.2

What is the minimum power of the transmitter?

Connector   Fusion splice   Connector

Transmitter   Receiver

20 m   60 m   3.74 m   20 m

Fiber lengths   All of these fibers have a loss of 3.5 dBkm^{-1}

Minimum acceptable power = −25 dBm

Step 1 – minimum power loss

The fiber:

The total length of the fiber is:

$$20\,\text{m} + 60\,\text{m} + 3.74\,\text{km} + 20\,\text{m} = 3.84\,\text{km}$$

The fiber has been checked and found to be of the same specification throughout with a loss of $3.5\,\text{dBkm}^{-1}$.

The total loss is therefore length × loss per unit length. This gives:

$$3.84 \times 3.5 = 13.44\,\text{dB}$$

The connectors:

According to the catalog, the loss for the type used is 1 dB per mated pair.

177

There are two mated pairs used, so the total loss is:

$$2 \times 1 = 2\,dB$$

The splices:

The fusion splice will be assumed to be 0.2 dB.

Total power loss:

The minimum value of power loss is therefore just the sum of these losses:

$$13.44 + 2 + 0.2 = 15.64\,dB$$

Step 2

Finding the maximum power loss:

The minimum power loss is 15.64 dB to which the aging and repair figures must be added.

Aging:

Consulting the catalog and where necessary, the suppliers, the aging losses used in this situation are:

▷ fiber = negligible
▷ connectors = 0.1 dB per mated pair. Therefore two pairs = 0.2 dB
▷ splice = negligible
▷ transmitter = 1 dB
▷ total aging loss = 1.2 dB

Repairs:

A loss of 1.5 dB is assumed. This will vary considerably according to the environment. This is just a guess.

Spare:

We will put in an extra 3 dB loss to take care of unforeseen situations, just in case.

The maximum power loss is:

▷ minimum loss = 15.64 dB
▷ aging = 1.2 dB
▷ repairs = 1.5 dB
▷ spare = 3 dB

The result is a maximum power loss of:

$$15.64 + 1.2 + 1.5 + 3 = 21.34\,dB$$

Step 3

The transmitter must supply enough power to overcome the worst-case losses and still meet minimum power level requirements of the receiver (Figure 16.3).

We must be careful to anticipate the likely value of the answer. It is all too easy to get a silly answer by blindly pressing the buttons on the calculator.

Figure 16.3

The transmitter output power must be at least −3.66 dBm

Maximum system loss = 21.34 dB   Minimum acceptable power = −25 dBm

Tx ———□———□——————————□— Rx
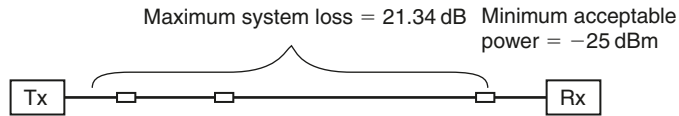
The receiver minimum power level is a large negative number of decibels. This means that the power level is very small. The transmitter output power must be greater than this and therefore the numerical value of the decibels must be less negative.

The minimum transmitter power = minimum receiver power + the losses. So, in our example:

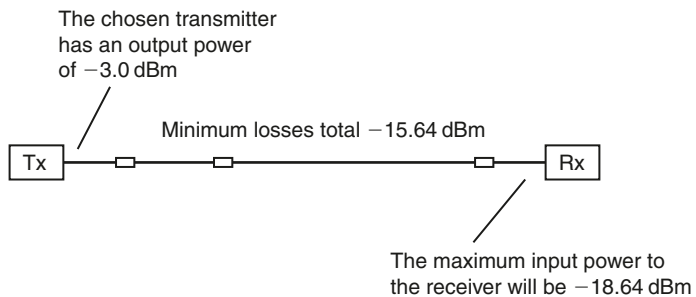minimum transmitter power $= -25 + 21.34 = -3.66$ dBm or 430.5 μW

Notice how the magnitude of the losses, 21.34 dB, is added as this represents additional power to be supplied by the transmitter.

The light source with the nearest value of output power available is 500 μW which converts to −3.0 dBm.

Now we need to look at the receiver input under minimum loss conditions as in Figure 16.4.

Figure 16.4

Make sure that the receiver will not be overloaded

The chosen transmitter has an output power of −3.0 dBm

Minimum losses total −15.64 dBm

Tx ———□———□——————————□— Rx

The maximum input power to the receiver will be −18.64 dBm

The maximum input power to the receiver occurs when the system losses are at their minimum level.

In our case:

maximum receiver power = transmitter power − minimum losses

So:

maximum receiver power $= -3 - 15.64 = -18.64$ dBm

In this case the loss figure is reducing the power available and is therefore subtracted.

Hopefully this would not be sufficiently high to damage the receiver. If it were, we could look for a more tolerant one or consider putting an attenuator into the system to use up the excess power. At a later date, due to repairs or modifications to the system, we may need more power. In this case, we could simply remove the attenuator. This also highlights the importance of maintaining adequate records. After several years, no one will remember that an attenuator was fitted into the system.
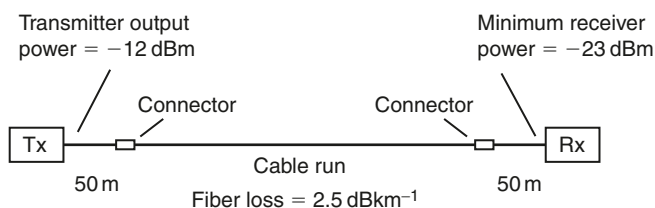
Another example

We have an existing system. We want to know by how much we could lengthen the cable without having to change the present transmitter and receiver.

Question

Given the system in Figure 16.5, how long could we make the optic fiber cable and still meet the minimum power specification for the receiver?

Figure 16.5
How much cable could we install?

Transmitter output power = -12 dBm
Minimum receiver power = -23 dBm

Connector   Connector

Tx   Rx

50 m   50 m

Cable run
Fiber loss = 2.5 dBkm^{-1}

Method of solving

Step 1

Find the total loss for the known system as it stands at the moment. This is done by gathering the data from catalogs, by measuring, or by consulting the suppliers.

Step 2

Add the aging loss, the likely repair losses and the spare 3 dB as before.

Step 3

Find the difference in the power of the transmitter output and the minimum receiver power so we know how much power can be used altogether. By subtracting the losses in Steps 1 and 2, we know how much is available for the cable.

Step 4

Once we know the power available for the link, it is an easy job to divide it by the loss per kilometer for the fiber to be used and hence find the safe maximum length for the cable.

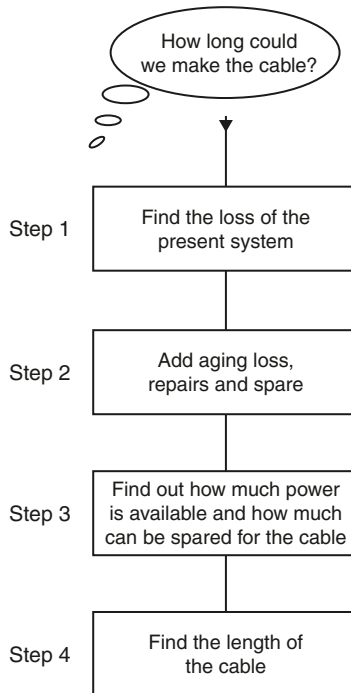**A worked solution following the steps itemized in Figure 16.6.**

Step 1

The present losses:

The two patchcords are each 50 m in length, giving a total of 100 m. Assuming the fiber used has a quoted loss of 2.5 dBkm^{-1}, this would mean a fiber loss of 0.25 dB.

Figure 16.6
How long
could we
make the
cable?

The mated pairs of connectors are assumed to be 0.2 dB for each pair. Total connector loss is therefore 0.4 dB.

The present losses amount to:

$$0.25 + 0.4 = 0.65\,\text{dB}$$

Step 2

Find the worst-case losses for the proposed system.

The aging loss:

$$0.1\,\text{dB per pair of couplers} = 0.2\,\text{total transmitter 1 dB}$$

For repairs, the assumed value is 2 dB (estimated).

Spare:

$$3\,\text{dB (as usual)}$$

So:

$$\text{total losses} = \text{losses from Step 1} + \text{aging loss} + \text{repair power} + \text{spare power}$$

In this case:

$$\text{total losses} = 0.65 + 1.2 + 2.0 + 3.0 = 6.85\,\text{dB}$$

Step 3

Find the power available for the required cable run.

Transmitter output power is -12 dBm and the minimum receiver input power is -23 dB, so there is a total of 11 dB available for the whole system. Of this 11 dB, we have already accounted for 6.85 dB.

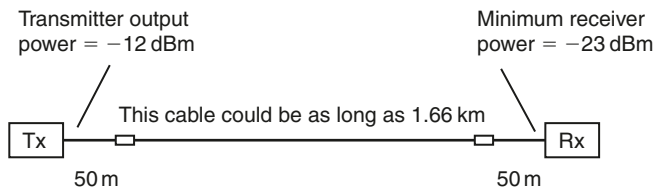The spare power for the link is:

$$11 - 6.85 = 4.15\,\text{dB}$$

Step 4

The fiber in use has a loss of 2.5 dBkm^{-1}, so the length that could be accommodated is:

$$\frac{4.15}{2.5} = 1.66\,\text{km}$$

as shown in Figure 16.7.

Figure 16.7

The maximum length of the cable

Transmitter output power = -12 dBm

Minimum receiver power = -23 dBm

This cable could be as long as 1.66 km

Tx — 50 m — Rx — 50 m

The usable bandwidth of optic fiber

To make a workable system we do not only need to be happy with the optical power budget but also to be confident that we can achieve a satisfactory data transfer rate, which means having a suitable bandwidth.

If we consult manufacturers' catalogs, bandwidths do not seem too much of a problem. The multimode graded index fiber is quoted as having a bandwidth of 300 MHz to 3 GHz. Single mode is even better at 500 MHz to 10 GHz.

Unfortunately, this tells only half of the story.

We saw in Chapter 7 that dispersion in fiber tends to spread out the pulses of light and they will merge until the information is lost. This puts an upper limit on how fast we can send the data. The magnitude of the dispersion problem increases with the length of the cable and so the transmission rate, and hence the bandwidth decreases with fiber length.

To make a real system we also need a light source and a receiver. They both have a finite switching speed and limit the transmission rate. There is no point in buying

a fiber able to deliver a bandwidth of 10 GHz if the receiver at the far end can only switch at 5 MHz.

Remember, it is the system bandwidth that we use, not just the fiber bandwidth so we need to investigate the effect of dispersion and the switching speed of the transmitter and the receiver.
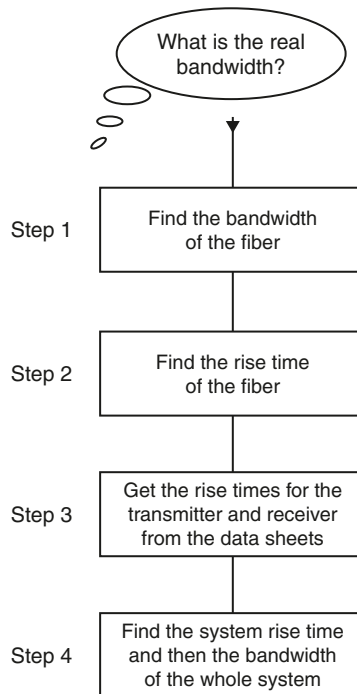
Multimode and single mode fibers respond a little differently and they need to be considered separately. The multimode case is slightly easier so we will look at that first.

The bandwidth of a multimode system

The method is summarized by Figure 16.8.

Figure 16.8

Finding the real bandwidth in a multimode system

Step 1

Find the bandwidth of the fiber.

We do this by obtaining the fiber bandwidth from its specification from the data sheet or catalog. A typical specification would be 500 MHz · km.

Note the units used, 500 MHz · km – this means that the bandwidth multiplied by the distance in kilometers comes to 500 MHz. So this particular fiber has a bandwidth of 250 MHz if it were only 2 km in length, but reduces to only 50 MHz if it were 10 km long. Notice already how the dream of a 500 MHz system is already fading.

183

Step 2

Find the fiber rise time (check Figure 14.3 for a reminder on rise time if necessary).

The rise time is the time taken for the light to increase from 10% to 90% of its final value. The higher the frequency of a waveform the shorter will be the rise time as shown in Figure 16.9. It is linked to the bandwidth as this is a measure of the highest frequency component in the signal transmitted along the fiber.

Figure 16.9
Short rise times need wide bandwidths
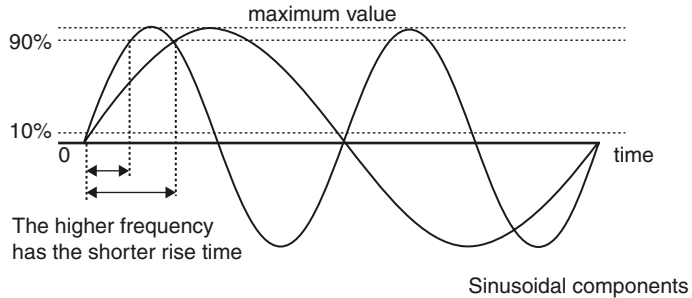
The higher frequency has the shorter rise time

Sinusoidal components

The rise time of the fiber is calculated using the bandwidth of the fiber that we found in Step 1:

$$t_r = \frac{0.35}{\text{bandwidth of the fiber}}$$

where t_r is an abbreviation for rise time. This formula, in common with some other system formulas, has been introduced without proof to avoid the usual long tedious justifications.

Step 3

We also need to know how fast the transmitter and the receiver are able to respond. Obviously, a sluggish device could spoil everything.

We find the rise time in the manufacturers' data. It is shown as response time or as t_r for rise time. A typical value for a laser is 0.3 ns and for an LED, 5 ns. Notice how much faster the laser is. Some receivers, particularly phototransistors, are not very brisk at all and need to be selected with care.

Step 4

We now have three different components, the light source, the fiber and the receiver, each with their own switching speed. When the electronic pulse is applied to the light source it will start to increase its light output power. The fiber follows at its own rate and finally the receiver electrical output starts to rise. It is not easy to see how these various reaction speeds would interact to produce an overall response for the system.

To do this, we combine the separate rise times:

$$t_{r_{SYS}} = \sqrt{t_{r_{RX}}^2 + t_{r_{TX}}^2 + t_{r_{FIBER}}^2}$$

This gives the rise time for the overall system.

Now we can get the bandwidth. To do this, we use the same basic formula as we used in Step 2, simply transposed to give the system bandwidth:
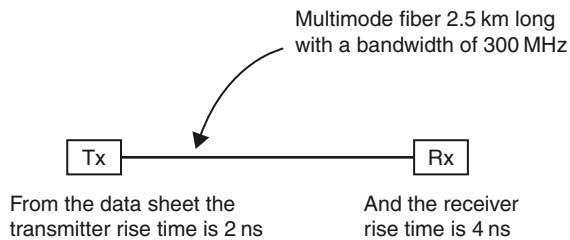
$$\text{Bandwidth} = \frac{0.35}{t_{r_{SYS}}}$$

A worked example – multimode

Find the usable bandwidth in the fiber optic system shown in Figure 16.10.

Figure 16.10
What is the usable band-width of this system?

Multimode fiber 2.5 km long with a bandwidth of 300 MHz

Tx — Rx

From the data sheet the transmitter rise time is 2 ns

And the receiver rise time is 4 ns

Step 1
Find the bandwidth of the fiber:

$$\text{Fiber bandwidth} = \frac{\text{quoted bandwidth}}{\text{length in km}}$$

$$\text{Fiber bandwidth} = \frac{300 \times 10^6}{2.5} = 120 \, \text{MHz}$$

Step 2
Find the fiber rise time:

$$\text{Rise time} = t_{r_{FIBER}} = \frac{0.35}{\text{fiber bandwidth}}$$

$$t_{r_{FIBER}} = \frac{0.35}{120 \times 10^6} = 2.9 \, \text{ns}$$

Step 3
Consult the data sheets to find the rise time of the light source and the receiver.

We will assume realistic values of 2 ns for the transmitter rise time and 4 ns for the receiver.

Step 4
We now find the system rise time by combining the three previous values.

To keep the calculation as simple as possible, we can work in nanoseconds throughout and simply remember to call the answer nanoseconds:

$$t_{r_{SYS}} = \sqrt{t_{r_{RX}}^2 + t_{r_{TX}}^2 + t_{r_{FIBER}}^2}$$

$$t_{r_{SYS}} = \sqrt{4^2 + 2^2 + 2.9^2} \text{ (all values in nanoseconds)}$$

$$t_{r_{SYS}} = 5.3 \text{ ns}$$
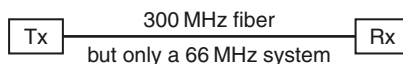
Now we can find the system bandwidth:

$$\text{System bandwidth} = \frac{0.35}{t_{r_{SYS}}}$$

$$\text{System bandwidth} = \frac{0.35}{5.3 \times 10^{-9}} = 66 \text{ MHz}$$

as seen in Figure 16.11.

Figure 16.11

The useful bandwidth doesn't only depend on the fiber

| Tx | 300 MHz fiber
but only a 66 MHz system | Rx |

It's interesting to see how the fiber is only one factor that determines the performance of the system. Our 300 MHz optic fiber has actually produced a system with a bandwidth of only 66 MHz. What a disappointment!

The bandwidth of a single mode system

We mentioned earlier that there are a couple of differences when it came to finding the bandwidth of a single mode system.

When we look at data sheets, we see that there are no bandwidth figures quoted for single mode fiber. Instead, they provide a figure for the dispersion characteristics and from this, we must calculate the bandwidth. It is not possible for the manufacturers to do this for us because the dispersion is dependent on the spectral width of the light source and the length of the fiber, and both of these are beyond their control.

Compared with the multimode calculation, we replace Step 1 but thereafter everything else is the same. The process is summarized in Figure 16.12.

Step 1

Find the dispersion:

The dispersion depends on the dispersion specification of the fiber, the spectral width of the light source and the fiber length.
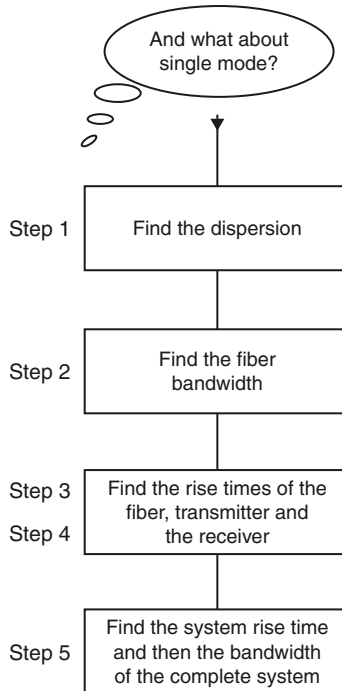
To find the dispersion we use the formula:

dispersion = dispersion specification for the fiber
    × spectral width of the light source × length of the fiber

The combination of these three factors, dispersion in picoseconds, spectral width in nanometers and length in kilometers produces the impressive unit of $ps\,nm^{-1}\,km^{-1}$ (read as picoseconds per nanometer per kilometer).

Figure 16.12

A single mode system – the real band-width

Step 1 — Find the dispersion

Step 2 — Find the fiber bandwidth

Step 3 / Step 4 — Find the rise times of the fiber, transmitter and the receiver

Step 5 — Find the system rise time and then the bandwidth of the complete system

Step 2

Find the fiber bandwidth:

This is simple enough:

$$\text{Fiber bandwidth} = \frac{0.44}{\text{dispersion figure}}$$

The resultant figure is usually in GHz but just as in multimode fiber, disappointment often follows unless the transmitter and receiver are carefully chosen.

The remaining stages of the calculation follow exactly the same pattern as we used for multimode fiber but it is outlined here for convenience.

Step 3

Find the fiber rise time.

The rise time of the fiber is calculated using the bandwidth of the fiber that we found in Step 2:

$$t_r = \frac{0.35}{\text{bandwidth of the fiber}}$$

Step 4

We find the rise time in the manufacturer's data. A typical value for a laser is 0.3 ns and for an LED is 5 ns. This is another advantage of using a laser for a single mode system where data rates are likely to be of importance.

Step 5

We now move on to find the overall response for the system.

As before, we combine the separate rise times:

$$t_{r_{SYS}} = \sqrt{t_{r_{RX}}^2 + t_{r_{TX}}^2 + t_{r_{FIBER}}^2}$$

This gives us the rise time for the overall system.

Now we can get the bandwidth. To do this, we use the same basic formula as we used in Step 3, simply transposed to give the system bandwidth:
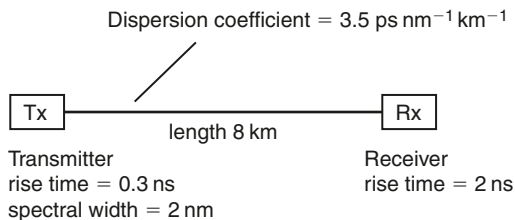
$$\text{Bandwidth} = \frac{0.35}{t_{r_{SYS}}}$$

A worked example

Calculate the system bandwidth for the single mode system shown in Figure 16.13.

Figure 16.13
The information needed to find the bandwidth of a single mode system

Dispersion coefficient $= 3.5$ ps nm^{-1} km^{-1}

Tx — length 8 km — Rx

Transmitter
rise time $= 0.3$ ns
spectral width $= 2$ nm

Receiver
rise time $= 2$ ns

Step 1

Find the dispersion:

To find the dispersion we use the formula:

dispersion = dispersion specification for the fiber
$\times$ spectral width of the light source $\times$ length of the fiber

Enter the values in pico seconds, nanometers and kilometers.

$$\text{dispersion} = 3.5 \times 2 \times 8 = 56 \, \text{ps} \, \text{nm}^{-1} \, \text{km}^{-1}$$

Step 2

Find the fiber bandwidth:

$$\text{Fiber bandwidth} = \frac{0.44}{\text{dispersion figure}}$$

$$\text{Fiber bandwidth} = \frac{0.44}{56 \times 10^{-12}}$$

$$\text{Fiber bandwidth} = 7.86 \, \text{GHz}$$

Step 3

Find the fiber rise time:

$$t_r = \frac{0.35}{\text{bandwidth of the fiber}}$$

$$t_r = \frac{0.35}{7.86 \times 10^9} = 44.53 \, \text{ps}$$

Step 4

From the data supplied, the transmitter rise time is 0.3 ns in this example, and the receiver rise time is 2 ns.

Step 5

The overall response for the system is given by the formula:

$$t_{r_{SYS}} = \sqrt{t_{r_{RX}}^2 + t_{r_{TX}}^2 + t_{r_{FIBER}}^2}$$

We can now enter our data but remember that the rise time of the fiber is in picoseconds and not nanoseconds. In order to be able to work in nanoseconds, we need to change the picoseconds into nanoseconds by dividing it by 1000 to give 0.0445 ns:

$$t_{r_{SYS}} = \sqrt{2^2 + 0.3^2 + 0.0445^2}$$
$$t_{r_{SYS}} = \sqrt{4.09}$$
$$t_{r_{SYS}} = 2.02 \, \text{ns}$$

This gives us the rise time for the overall system.

Now we can find the system bandwidth:

$$\text{System bandwidth} = \frac{0.35}{t_{r_{SYS}}}$$

$$\text{System bandwidth} = \frac{0.35}{2.02 \times 10^{-9}} = 173.3 \, \text{MHz}$$

The lesson to be learned here is that the light source performance and the receiver rise time are really significant if the full potential of a single mode system is to be achieved.

In this example system, by looking at the system rise time formula:

$$t_{r_{SYS}} = \sqrt{2^2 + 0.3^2 + 0.0445^2}$$

we can see that the 2 ns due to the receiver response time is significantly greater than the 0.3 ns of the laser and the very small 0.0445 due to the fiber. It follows then, that little would be achieved by spending more money on better fiber or indeed a faster laser. Changing the receiver to one with a 1 ns response time would increase the system bandwidth to approximately 335 MHz: a good investment.

Quiz time 16

In each case, choose the best option.

1   Reducing the length of a multimode fiber would:

(a) decrease the transmitter rise time

(b) decrease the system bandwidth

(c) increase the bandwidth of the system

(d) increase the system rise time

2   Changing the spectral width of the light source would affect the:

(a) fiber bandwidth in a single mode system

(b) system bandwidth of a multimode system but not a single mode one

(c) aging losses

(d) number of likely repairs

3   If the transmitter and the receiver rise times were 0.5 ns and 1.5 ns respectively, and the fiber rise time was 25 ps, the system rise time would be approximately:
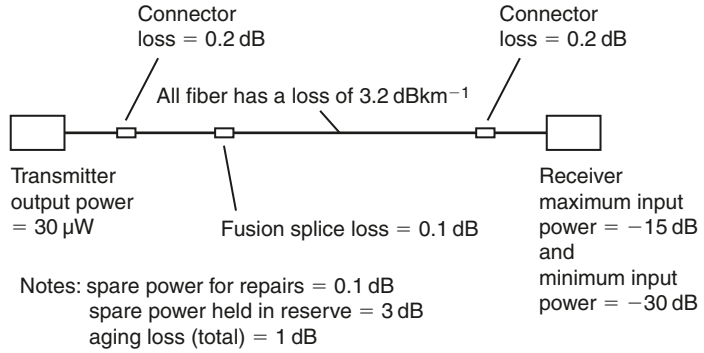
(a) 25.05 ns

(b) 1.42 ns

(c) 1.58 ns

(d) 5.19 ns

4   Referring to the multimode system in Figure 16.14, the maximum usable length of fiber would be approximately:

(a) 1.2 km

(b) 2.2 km

Figure 16.14

Question 4

Connector
loss = 0.2 dB

Connector
loss = 0.2 dB

All fiber has a loss of 3.2 dBkm^{-1}

Transmitter
output power
= 30 µW

Fusion splice loss = 0.1 dB

Receiver
maximum input
power = −15 dB
and
minimum input
power = −30 dB

Notes: spare power for repairs = 0.1 dB
spare power held in reserve = 3 dB
aging loss (total) = 1 dB

(c) 3.2 km

(d) 4.2 km

**5   If the dispersion figure for a single mode fiber is known to be 44 ps,
the bandwidth of the fiber would be:**

(a) 10 GHz

(b) 7.95 GHz

(c) 100 MHz

(d) 795 MHz