7

Dispersion and our attempts to prevent it

In the last chapter we looked at a few causes of power loss which tend to limit the useful transmission range. Unfortunately the mere fact that we can send light to the other end of the system is not enough, we have also to ensure that the data is still decipherable when it arrives.

We have met the effect in public address systems. As soon as the announcement ends, people turn to one another and say 'What did she say?' 'What was that all about?'. We can't make out what is being said. Hearing the sound is no problem, there is plenty of volume and increasing it further would not help and would probably make the situation worse.

The problem is that the sound is arriving by many separate paths of different lengths, and parts of each sound are arriving at different times. In most cases we can handle this well and automatically compensate for any multiple reflections, but in severe situations it simply overloads our brain's computing capability. Indeed, we are so clever at handling this situation that we can use it to 'sense' the size of a room. When we step over the threshold the spurious echoes cease and we know that we are outside.

Optic fibers suffer from a very similar effect, called *dispersion*.

Dispersion

Imagine we launch two different rays of light into a fiber. Now, since both rays are traveling in material of the same refractive index they must be moving at the same speed. If we follow two different rays of light which have entered the core at the same time, we can see that one of them, Ray A in Figure 7.1, will travel a longer distance than the other, Ray B. The effect of this is to cause the pulse of light to spread out as it moves along the fiber – as the ray taking the shorter route overtakes the other.

This spreading effect is called dispersion (Figure 7.2).

Figure 7.1 Ray B will arrive first

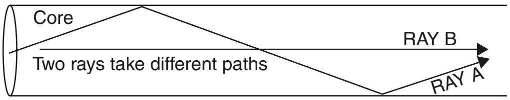
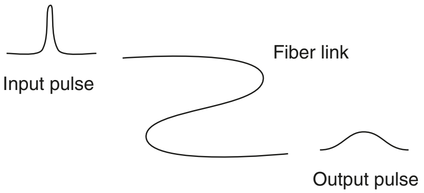


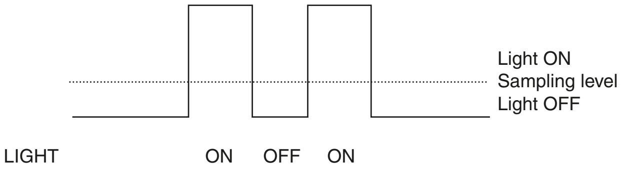
Figure 7.2 The pulse spreads out



The effect on the data

The data can be corrupted by dispersion. If we send a sequence of ON-OFF-ON pulses, it would start its life as an electronic signal with nice sharp edges as in Figure 7.3.

Figure 7.3 Electronic pulses controlling the light source



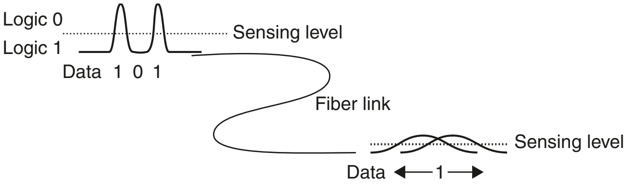
These pulses are used to switch a light source, usually an LED or a laser and the resultant pulses of light are launched into the fiber.

Dispersion causes the pulses to spread out and eventually they will blend together and the information will be lost (Figure 7.4).

We could make this degree of dispersion acceptable by simply decreasing the transmission frequency and thus allowing larger gaps between the pulses.

This type of dispersion is called *intermodal dispersion*. At this point, we will take a brief detour to look at the idea of modes.

Figure 7.4 Dispersion has caused the pulses to merge



Modes

The light traveling down the fiber is a group of *electromagnetic* (EM) waves occupying a small band of frequencies within the electromagnetic spectrum, so it is a simplification to call it a ray of light. However, it is enormously helpful to do this, providing an easy concept – some framework to hang our ideas on. We do this all the time and it serves us well providing we are clear that it is only an analogy. Magnetic fields are not really lines floating in space around a magnet, and electrons are not really little black ball bearings flying round a red nucleus.

Light therefore, is propagated as an electromagnetic wave along the fiber. The two components, the electric field and the magnetic field, form patterns across the fiber. These patterns are called *modes of transmission*. Modes means methods – hence methods of transmission. An optic fiber that carries more than one mode is called a *multimode* fiber (MM).

The number of modes is always a whole number.

In a given piece of fiber, there are only a set number of possible modes. This is because each mode is a pattern of electric and magnetic fields having a physical size. The dimensions of the core determine how many modes or patterns can exist in the core – the larger the core, the more modes.

The number of modes is always an integer; we cannot have incomplete field patterns. This is similar to transmission of motor vehicles along a road. As the road is made wider, it stays as a single-lane road until it is large enough to accommodate an extra line of vehicles whereupon it suddenly jumps to a two-lane road. We never come across a 1.15-lane road!

How many modes are there?

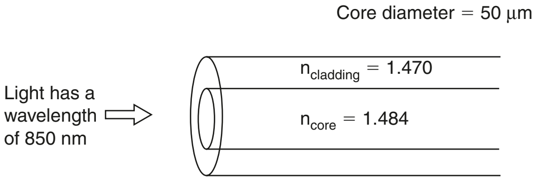
The number of modes is given (reasonably accurately) by the formula:

$$\text{Number of modes} = \frac{\left(\text{Diameter of core} \times \text{NA} \times \dfrac{\pi}{\lambda}\right)^2}{2}$$

where NA is numerical aperture of the fiber and λ is the wavelength of the light source.

Let's choose some likely figures as in Figure 7.5 and see the result.

Figure 7.5
How many modes are in the core?



Method

Find the numerical aperture

$$\mathrm{NA} = \sqrt{(1.484)^2 - (1.470)^2}$$

So:

$$\mathrm{NA} = 0.203 \text{ (a typical result)}$$

Insert the figures into the formula:

$$\text{Number of modes} = \frac{\left(50 \times 10^{-6} \times 0.203 \times \dfrac{\pi}{850 \times 10^{-9}}\right)^2}{2}$$

Tap it into a calculator and see what comes out:

$$\text{number of modes} = 703.66$$

The calculator gave 703.66 but we cannot have part of a mode so we have to round it down. Always round down as even 703.99 would not be large enough for 704 modes to exist.

Each of the 703 modes could be represented by a ray being propagated at its own characteristic angle. Every mode is therefore traveling at a different speed along the fiber and gives rise to the dispersion which we called intermodal dispersion.

How to overcome intermodal dispersion

We can approach the problem of intermodal dispersion in two ways. We could redesign the fiber to encourage the modes to travel at the same speed along the fiber or we can eliminate all the modes except one – it can hardly travel at a different speed to itself! The first strategy is called *graded index* optic fiber.

Graded index fiber

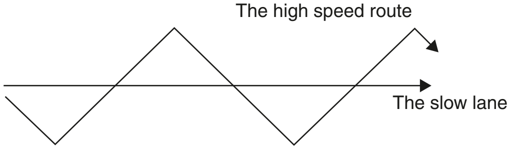
This design of fiber eliminates about 99% of intermodal dispersion. Not perfect – but a big improvement.

The essence of the problem is that the ray that arrives late has taken a longer route. We can compensate for this by making the ray that takes the longer route move faster. If the speed and distance of each route is carefully balanced, then all the rays can be made to arrive at the same time – hence no dispersion. Simple. At least in theory (Figure 7.6).

We often meet this while driving. Do we take the shorter route and creep through the city center? Or do we take the longer, faster route on the by-pass? So often we find it makes little difference, the extra distance is offset by the extra speed.

The speed that light travels in the core is determined by the refractive index.

Figure 7.6
They arrive at (almost) the same time



The formula is:

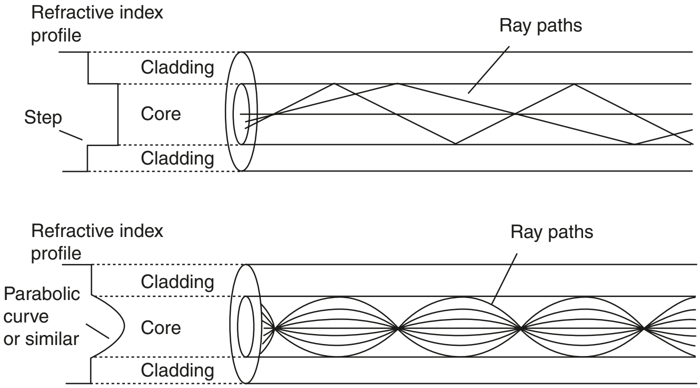
$$\text{Speed of light in the material} = \frac{\text{speed of light in free space}}{\text{refractive index}}$$

The solution to our problem is to change the refractive index progressively from the center of the core to the outside. If the core center has the highest refractive index and the outer edge has the least, the ray will increase in speed as it moves away from the center.

The rate at which the refractive index changes is critical and is the result of intensive research. A parabolic profile is often employed but there are many others available in specialized fibers.

The GI (graded index) and the SI (step index) profiles are shown in Figure 7.7. Step index fibers are the basic type in which the core has a set value of refractive index and is surrounded by the cladding, with its lower value. This results in the characteristic step in the value of the refractive index as we move from the core to the cladding.

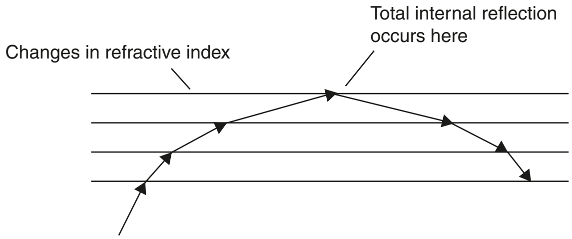
Figure 7.7
Two types of fiber: (Top) step index fiber; (Bottom) graded index fiber



We can see that, in the GI fiber, the rays each follow a curved path. This is one of the results of the change in refractive index as we move away from the center of the core.

We can consider the core to be made of a whole series of discrete changes in refractive index as shown in Figure 7.8. At each boundary there is a change in refractive index and the light ray is refracted slightly. Every time the ray is refracted the angle of incidence increases. Eventually the ray will approach a layer at an angle greater than the critical angle and reflection occurs.

Figure 7.8 The ray is refracted slightly at each boundary



It is now approaching the core and as it passes through the layers of increasing refractive indices the curvature will again increase. This process will be repeated as it crosses the fiber and the light will be made to follow a curved path along the core. Notice how some rays (modes) are restricted to the center (low speed) area of the core and some extend further out into the faster regions.

It is important to appreciate that, in a real GI fiber, change in the refractive index is smooth and continuous. It is not really arranged in layers as is suggested by the diagram. The result is that the light suffers an infinite number of small refractions and has the effect of making the light bend in the smooth curves we saw in Figure 7.7, rather than discrete steps at each layer.

The number of modes in a graded index fiber is half that found in a step index fiber so in the mode formula (see page 64) the bottom line should read the figure 4, rather than the 2 shown. The practical result of this is that a step index fiber will hold twice the number of modes and hence accept twice the input power from a light source than would a graded index fiber. However, the dispersion advantage of the graded index still makes a graded index desirable for multimode fibers.

Single mode (SM) fiber

Intermodal dispersion is the result of different modes (rays) traveling at different speeds. The easy way to avoid this is to have only one mode.

How to get one mode and solve the problem

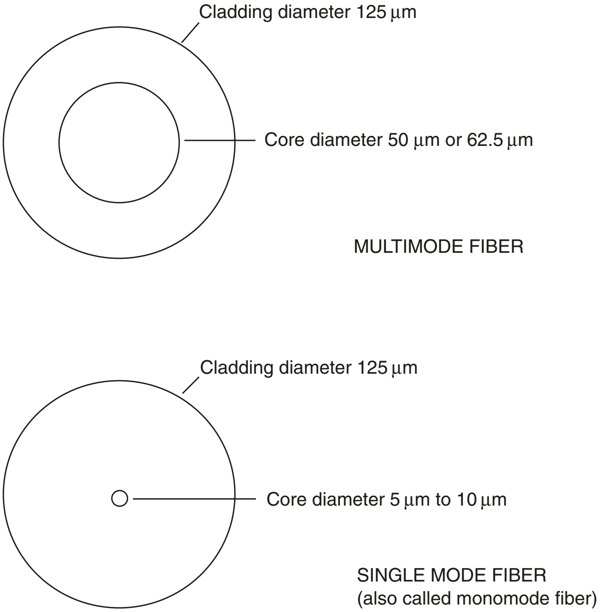
If we have another look at the formula for the number of modes:

$$\text{Number of modes} = \frac{\left(\text{Diameter of core} \times \text{NA} \times \dfrac{\pi}{\lambda}\right)^2}{2}$$

we can see that we could decrease the number of modes by increasing the wavelength of the light. However this alone cannot result in reducing the number of modes to one. Changing from the 850 nm window to the 1550 nm window will only reduce the number of modes by a factor of 3 or 4 which is not enough on its own. Similarly, a change in the numerical aperture can help but it only makes a marginal improvement.

We are left with the core diameter. The smaller the core, the fewer the modes. When the core is reduced sufficiently, the number of modes can be reduced to just one. The core size of this SM, or single mode fiber, is between 5 μm and 10 μm. Figure 7.9 shows an MM and an SM fiber drawn to scale. The difference in the core size is clearly visible.

Figure 7.9
It's easy to see the difference



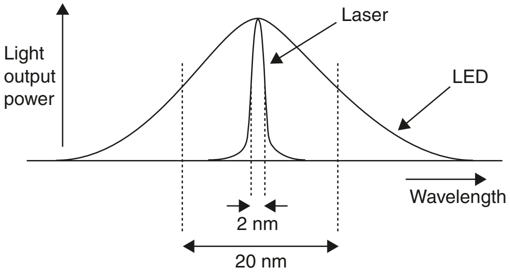
Intramodal (or chromatic) dispersion

Unfortunately intermodal dispersion is not the only cause of dispersion.

We know that light of different wavelengths is refracted by differing amounts. This allows raindrops to split sunlight into the colors of the rainbow. We are really saying that the refractive index, and hence the speed of the light, is determined to some extent by its wavelength.

A common fallacy is that a laser produces light of a single wavelength. In fact it produces a range of wavelengths even though it is far fewer than is produced by the LED, the alternative light source (Figure 7.10).

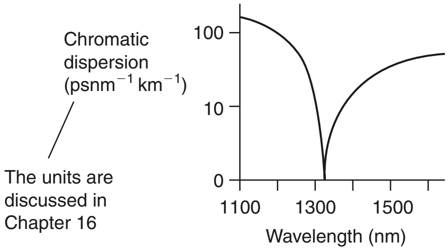
Figure 7.10
The laser has a narrow spectral width



This is unfortunate as each component wavelength travels at a slightly different speed in the fiber. This causes the light pulse to spread out as it travels along the fiber – and hence causes dispersion. The effect is called *chromatic dispersion*.

Actually, chromatic dispersion is the combined effect of two other dispersions – *material dispersion* and *waveguide dispersion*. Both result in a change in transmission speed; the first is due to the atomic structure of the material and the second is due to the propagation characteristics of the fiber. Any further investigation will not help us at the moment and is not pursued further.

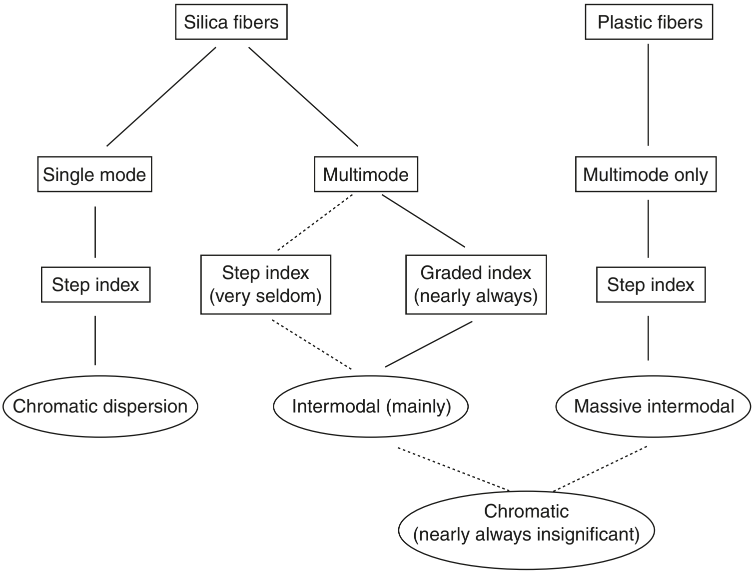
Figure 7.11 The effect of wavelength



One interesting feature of chromatic dispersion is shown in Figure 7.11. The value of the resulting dispersion is not constant and passes through an area of zero dispersion. This cannot be used to eliminate dispersion altogether because the zero point only occurs at a single wavelength, and even a laser produces a range of wavelengths within its spectrum.

By fiddling about with the dimensions of the core and the constituents of the fiber, we can adjust the wavelength of the minimum dispersion point. This is called *optimizing* the fiber for a particular wavelength or window.

Figure 7.12 Dispersion – a summary



Be careful not to muddle intermodal dispersion with intramodal dispersion.

- ▷ *inter* means between; *Intermodal* – between modes
- ▷ *intra* means within; *Intramodal* – within a single mode.

The alternative name of 'chromatic', to do with color or frequency, is less confusing.

Although chromatic dispersion is generally discussed in terms of a single mode fiber, it does still occur in multimode fiber but the effect is generally swamped by the intermodal dispersion.

Dispersion is summarized in Figure 7.12.

Quiz time 7

In each case, choose the best option.

1 Dispersion:

(a) causes the core to spread out and get wider as the pulse is transmitted along the fiber

(b) results in the wavelength of the light increasing along the fiber

(c) is the lengthening of light pulses as they travel down the fiber

(d) cannot occur with a laser light source

2 An SI MM fiber has a core of 62.5 μm diameter and a numerical aperture of 0.2424. The number of modes that would occur using a light of wavelength of 865 nm would be:

(a) 1

(b) 378

(c) 1513.78

(d) 1513

3 Intramodal dispersion:

(a) only occurs in multimode fiber

(b) is also called chromatic dispersion

(c) does not occur in multimode fiber

(d) could not occur in an all-plastic fiber

4 If the wavelength of the transmitted light were to be decreased, the number of modes would:

(a) increase

(b) decrease

(c) remain the same

(d) halve in a graded index fiber

5 The refractive index of a GI fiber:

(a) is at its highest value at the center of the core

(b) is usually higher in the cladding than in the core

(c) increases as we move away from the center of the core

(d) has a value of 4 instead of the 2 common in step index fibers

8

Real cables

The optic fiber manufacturers provide the primary coated optic fiber. At this stage, the fiber is easily broken between finger and thumb and is typically only 250 μm in diameter.

The cable manufacturers then enclose the optical fiber (or fibers) in a protective sleeve or sleeves. These sleeves are often referred to as *jackets*, or *buffers* – the exact terminology differs a little according to manufacturer. Once enclosed, the assembly is then referred to as a *cable*.

The cost of installing the cable on site is much greater than the cost of the optic fiber alone, so it makes good sense to provide plenty of spare system capacity to allow for failures or expansion in the traffic to be carried. Extra fibers that are installed but not used do not deteriorate, so they can be left until required and are sometimes called *dark*, *spare* or *redundant* fibers. Nowadays, traffic that decreases in volume is a rare event indeed.

Although we could insist on buying a cable containing almost any number of fibers, it is generally less expensive and easier to buy standard sizes.

Small cables usually have a fiber count of 1, 2, 4 or 8.

Medium size cables have counts increasing in multiples of 6 or 8 to give typical sizes of 12, 18, 24, 30 and 36.

Larger cables increase in steps of 12 to give 48, 60, 72, etc.

The degree of protection depends on the conditions under which the cable is to operate. Some cables will live a luxurious life – warm, dry and undisturbed asleep in a duct in an air-conditioned office, while others are outside in the real world. These may well be submerged in water or solvents, attacked by rodents, at sub-zero temperatures or being crushed by earthmovers on a construction site.

Strength members

If we pull a length of fiber through a duct, the outer cover would stretch and the pulling load would be taken by the glass fiber, which would break. To prevent this the cable is reinforced by adding strength members. These are strong, low stretch materials designed to take the strain. The strength members used are usually fibers of aramid yarn, best known by their brand name of Kevlar (® Dupont Inc.), for light duty cable. For heavy duty cables we might expect to see fiber glass rods or steel wires. Kevlar is a very fine, yellow, silky fiber which is, weight for weight, about four times stronger than steel. It resists crushing and being pierced which makes it popular for another of its applications – bulletproof clothing. Unfortunately, it stretches too much to replace steel altogether and is also quite expensive.

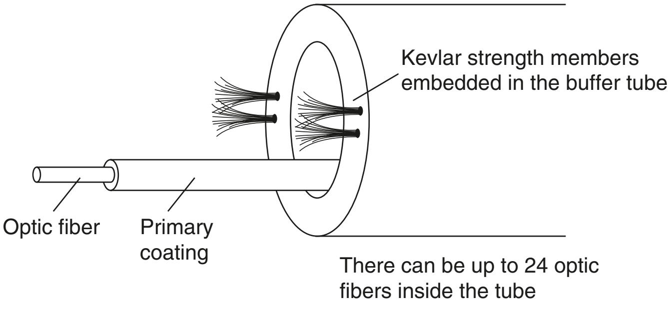
Basic choice of cable design

There are two distinctly different methods used to protect the optic fibers. They are referred to as *loose tube* and *tight buffer* designs. We will have a look at these in a moment. There is a tendency for tight-buffer cables to find employment within buildings and loose-tube designs to be used externally. This is not a 'golden rule', just a bias in this direction.

Loose-tube construction

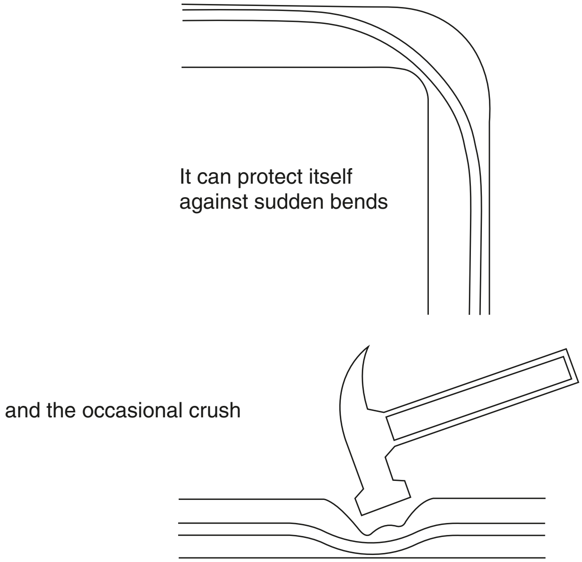
A hollow polymer tube surrounds the optic fiber as can be seen in Figure 8.1. The internal diameter of this tube is much greater than the diameter of the optic fibers that simply lie inside it. There is room for more than one fiber and as many as twenty-four optic fibers can run through the same tube. Heavy duty versions are available with hundreds of fibers shared amongst dozens of tubes.

Figure 8.1
Loose-tube construction



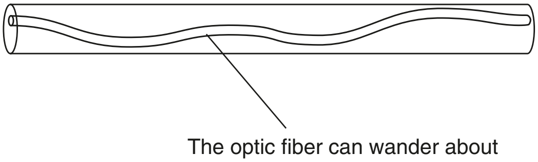
The main feature is that the optic fiber is thus free to move about as it wishes. The benefit of this is that its natural springiness allows the optic fiber to take the path of least strain and allows the fiber to expand and contract with changes of temperature. Figure 8.2 shows how the fiber is able to take the route with the

Figure 8.2 Some benefits of loose-tube construction



largest radius of curvature and help to protect itself from bending losses. Under normal, non-stress conditions the optic fiber(s) tend to snake lazily about inside the buffer tube and this results in the optic fiber itself being slightly (about 1%) longer than the buffer tube. This has the further advantage that the cable can be stretched by about 1% during installation without stressing the optic fiber (Figure 8.3).

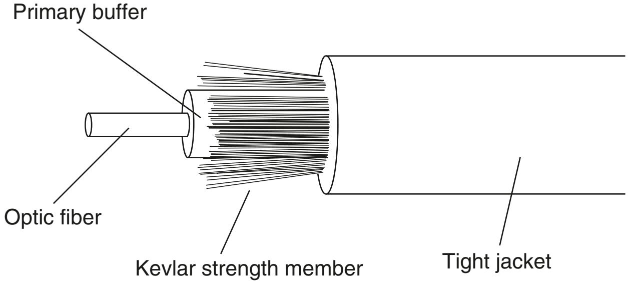
Figure 8.3 The optical fiber is up to 1% longer than the tube



Tight-buffer construction

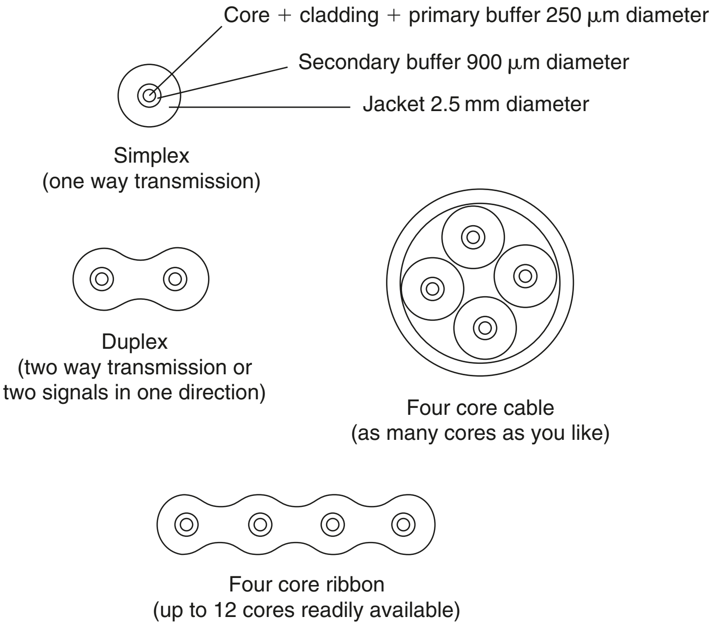
In this case, a jacket is fitted snugly around the optic fiber in the same way that electrical cables are coated in plastic. This provides protection while allowing flexibility. This form of construction (shown in Figure 8.4) is normally, but again

Figure 8.4 Tight-buffer construction



not exclusively, used for indoor installations. Tight-jacketed cables come in a variety of forms to suit the installation requirements and may be single mode or multimode. A small selection is shown in Figure 8.5.

Figure 8.5 Tight-jacketed cables (strength members omitted for clarity)



Plastic optic fiber cable is always tight buffered.

There are three options regarding the strength members. They can be placed immediately under the outer jacket or added around each individual optic fiber within their own jacket, sometimes referred to as a *sub-jacket*.

Heavier cables often have an additional strength member in the center.

Breakout cable

The advantage of the latter approach is that the outer jacket can be stripped off leaving us with individual cables, each with its own strength members. This type is called *breakout cable*. The main cable is installed, perhaps as far as an office space via ceiling ducts and then, by stripping off the outer jacket, the individual cables can be fed to each point of use. This style of cable however is seen as expensive and is not that popular anymore.

Hybrid cable

We cannot transmit electrical power along an optic fiber and so in some cases it is necessary to include copper conductors to power repeaters or other instruments at the far end. Such *hybrid cable* can be custom built and may well include many different types of optic fiber, power cables of different voltage, copper coaxial cables and anything else that you feel like. The resulting cable can be bulky, heavy and very, very expensive.

Cable design – other factors that may need considering

Fire precautions

For use within buildings, the outer sheath is usually PVC (polyvinyl chloride) – the same plastic coating that is used for electrical wiring.

The PVC is often treated to reduce the fire hazards. As we know from the publicity surrounding smoke detectors in buildings, toxic fumes and smoke are an even greater hazard than the fierce burning of the PVC. To reduce the fire risk, the PVC is treated to reduce the rate of burning and is referred to as flame retardant. In addition, to reduce the other risks, it is available with low smoke and gas emission.

Chlorine (i.e. the ‘C’ in PVC) is from a branch of elements called halogens, which also contains fluorine, bromine and iodine. Halogens are often added to hydrocarbon plastics to aid flexibility, reduce flammability and to act as stabilizers and give a number of other benefits. PVC is a classic example of a halogenated plastic.

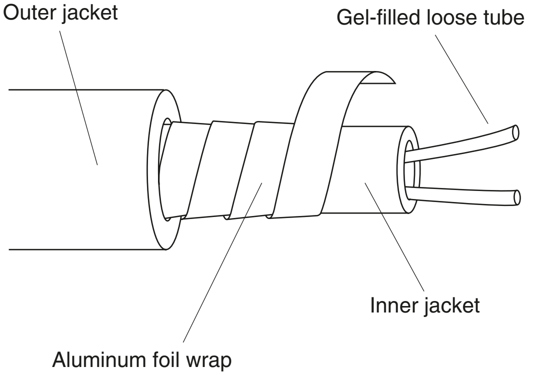
Over the last ten years the toxicity caused by the halogen-laden smoke from burning PVC has become apparent. The smoke is extremely toxic and acidic. This has led to the development of ranges of PVC-free cables sheathed in ‘zero-halogen’ materials and bearing names such as LSF (low smoke and fume), LFH (low fire hazard) and LSOH (low smoke, zero halogen) and any number of other abbreviations. Unfortunately there is no standard or regulated terminology used in the industry for this range of products and the buyer needs to display some *caveat emptor* when confronted with manufacturers’ claims and should ask exactly what IEC or CENELEC standards the cables actually conform to. More definitions can be obtained from www.ThePhysicalLayer.com. LSOH cables have taken about 15% of the European market for indoor data cables and command price premiums of 20 to 50% over their PVC counterparts.

Different rules apply in America where the National Electrical Code defines strictly applied codes for General Purpose, Riser and Plenum grades of cables. The relevant American standards are defined by the UL organization such as UL910 for plenum grade cables. A plenum in this context means an architectural space where air is forced, or allowed, to move, e.g. a ceiling void used as the return path for air-conditioning (Elliott and Gilmore, 2002).

Moisture

Unfortunately, PVC is not completely impervious to water and, as we have seen previously, large losses can result from such ingress. Cable for external use is normally sheathed in polyethylene and is usually of loose tube construction. An additional precaution is to fill the loose tubes and other spaces within the cable with a silicon or petroleum based gel. This gel is waterproof and thixotropic and flows into any spaces. In severe conditions where the cable is permanently submerged even several layers of polyethylene are found not to be totally waterproof. In these conditions, an aluminum foil wrap is placed immediately under the outer jacket (Figure 8.6).

Figure 8.6
A waterproof cable (strength members omitted for clarity)



Ultraviolet protection

Sunlight and other sources of UV light tend to degrade many plastics, including standard polyethylene and PVC, in the course of time. In most cases, making the outer sheath from UV stabilized polyethylene is sufficient, but for extreme situations a metal-sheathed cable is used.

Hydrocarbons

Hydrocarbons are organic compounds of hydrogen and carbon and include solvents, oils, benzene, methane and petroleum. Polyethylene provides poor protection against hydrocarbons and more exotic materials such as nylon or PTFE (Teflon) may be used. For the ultimate in protection against these agents, a lead inner sheath can be added under the polyethylene outer layer.

Radiation

Optical fibers, especially multimode, are sensitive to ionizing radiation, e.g. X-rays, gamma rays, electron beams, etc. The fibers tend to go dark and hence the attenuation rises. Fibers that are expected to withstand radiation, such as in nuclear power plant monitoring, in close proximity to X-ray sources, in space craft or even military systems expected to survive a nuclear Armageddon, must either be protected by lead sheathing or picked from specialist ranges of radiation 'pre-hardened' fibers.

Locating the correct fiber

In multi-core cables, the buffers are usually colored to reduce the chance of incorrect connection during installation.

Typical colors used for the first 12 fibers are listed below.

Fiber number	*Color*
1	blue
2	orange
3	green
4	brown
5	slate
6	white
7	red
8	black
9	yellow
10	violet
11	rose
12	aqua

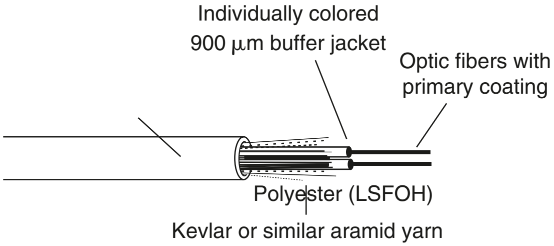
When we come to the 13th fiber we start at blue again but we add a thin black stripe called a tracer. The 14th fiber would be orange with a black tracer. What color would we use for the fiber number 20? Now, there's a problem. Using the above method, we would expect black with a black tracer. We break from the sequence and use black with a yellow tracer. Another method, used in loose tube cables, is to wrap individual bundles of fibers with different colored threads.

Mechanical damage

Mechanical support and strength members are not the same even though, in some cases, both functions can be performed by the same elements. Strength members are present to prevent the cable being excessively stretched but mechanical damage can involve other forms of abuse such as being crushed or cut.

In light duty cables as used in buildings, both functions can be achieved by a layer of Kevlar or similar material placed under the outer jacket (Figure 8.7).

Figure 8.7 Light duty indoor distribution cable



We may also provide some localized protection such as when the fiber is fed under a carpet, for instance. It will be walked on and crushed by furniture being moved. A protective strip is shown in Figure 8.8 and is very similar to those used to protect electrical wiring.

In situations beyond the ability of Kevlar, the normal form of protection is to add a layer, or several layers, of metallic tape or galvanized wire under the outer sheath as in Figure 8.9.

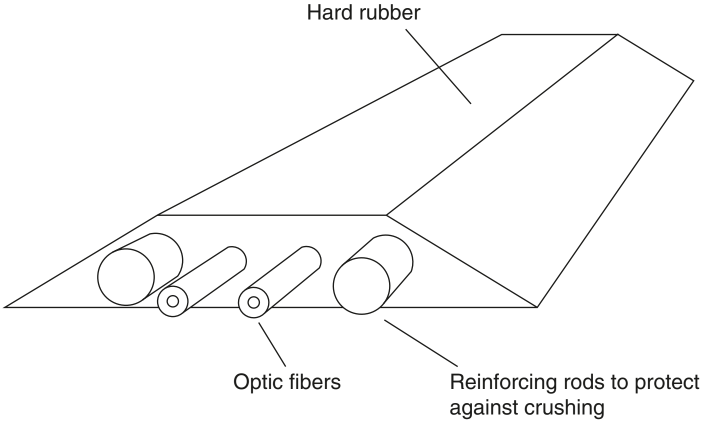


Figure 8.8 A form of localized protection

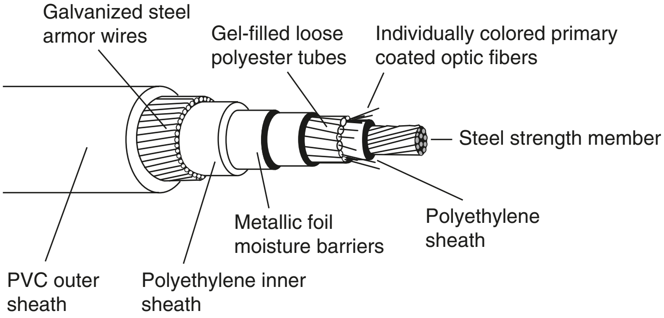


Figure 8.9 An external direct burial cable

The cable may have to survive crushing forces from surface traffic or earth movement or perhaps being picked up by a mechanical digger. It may be laid across a river or indeed an ocean. In the latter case, the cable is initially buried but for most of its distance it is simply dropped onto the ocean floor to take its chance. The enormous cost of location, recovery and repair make extra mechanical protection a very good investment. It is, of course, a matter of judgment as to the degree of protection that a particular cable requires. Adding further protection has the inevitable result of increasing the size and weight which will mean that the strength members would need upgrading to prevent damage during installation.

It is worth mentioning that the galvanized wires, added for additional crush resistance and protection against abrasion, are wound around the cable in a spiral. The result of this wrapping technique is that this additional layer does little to assist the strength members, and certainly could not replace them. As we know, if we pull on a spiral, such as a spring, it gets longer. Applied to a cable, it would mean that pulling forces would cause the cable to lengthen until the fibers break.

The cost of the optic fiber within the outdoor cable is an insignificant part of the whole. It pays then to install considerable spare capacity in the form of extra optic fibers to allow for failures or expansion of the traffic carried in the future.

The spare fibers do not degrade by laying around unused but to add an extra fiber after installation would mean laying a whole new cable.

Rodents

One form of mechanical damage which may need to be addressed in some situations is rodent damage. In both fiber and electrical cables they gnaw away until they either break through the optic fiber or they reach the live conductor and the cable takes its revenge.

Rodent attack can be lessened by using a very hard plastic for the outer sheath or, more usually, relying on the layer of galvanized wire strands that was added for general mechanical protection. Nowadays a lower cost form of armoring is to use a corrugated steel tape. An alternative approach is to install the cable in a rodentproof duct.

Installation tension

As the name suggests, this is a measure of how hard we can pull the cable during installation without causing damage. The force is measured in Newtons (N). The quoted values start at about 100 N for lightweight internal cables and extend to 10 000 N or more for ruggedized cables.

So what does all this mean? How big is a Newton?

For those of us who enjoy the unlikely story of Sir Isaac Newton sitting under an apple tree, it may be interesting to know that to pick up an average sized eating apple he would have applied a force of about 1 N. An equally unscientific measure is achieved by taking off your jacket, rolling up your sleeves, taking a firm grip on the cable and pulling hard until you break out in a gentle sweat. We are now looking at a force in the region of 250 N. Slightly nearer the mark is to remember that about 10 N is needed to lift a 1 kg (2.2 lb) weight.

Both eating-apples and people come in a wide range of sizes. For this reason, the apparatus for pulling the cables is fitted with adjustable tension and mechanical fuses to prevent damage to the cable.

Weight

Expressed in kilograms per kilometer ($\text{kg} \cdot \text{km}^{-1}$). There is obviously a wide range of weights depending on the degree of protection built into the cable. Light duty indoor cable designs with the Kevlar strength members result in weights around $20\,\text{kg} \cdot \text{km}^{-1}$ and the armored external cables are in the order of $500\,\text{kg} \cdot \text{km}^{-1}$. Hybrid cables which include copper cores can be very much heavier.

Bending radius

To prevent damage to the cable and possible bending losses, the minimum bend radius is always quoted in the specification. One interesting point is that two different figures are stated – a tighter bend is allowed for long-term use since the cable is no longer under stress once installation is complete. For a lightweight cable the figures are about 50 mm for long-term use and 70 mm during installation, and for external armored cable the figures are around 175 mm and 350 mm respectively.

Temperature range

Three temperatures may be offered in a specification:

- installation range, typically 0°C to +60°C
- operating range, −30°C to +70°C
- storage range, −40°C to +80°C.

The installation range is the most restricted because the cable will be under stress during this time.

Typical examples

To bring it all together, here are two typical cables. The first is a lightweight internal tight-jacketed cable and the other is an external armored cable suitable for direct burial.

Lightweight internal cable – Figure 8.7

Cable diameter	4.8 mm
Minimum bending radius	
long term	40 mm
installation	60 mm
Installation tension	
long term	250 N
installation	800 N
Weight	$19\ \mathrm{kg} \cdot \mathrm{km}^{-1}$
Temperature range	
installation	0°C to +60°C
static operation	−10°C to +70°C
storage	−20°C to +80°C

External direct burial cable – Figure 8.9

Cable diameter	14.8 mm
Minimum bending radius	
long term	150 mm
installation	225 mm
Installation tension	
long term	600 N
installation	3000 N
Weight	$425\ \mathrm{kg} \cdot \mathrm{km}^{-1}$
Temperature range	
installation	0°C to +60°C
static operation	−10°C to +60°C
storage	−20°C to +70°C

Installation of the cable

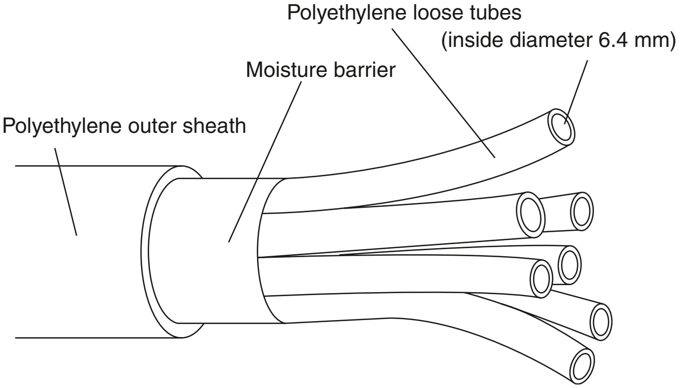
Most fiber is installed by traditional pulling techniques developed for copper cable. A pulling tape is inserted into the duct and is attached to the end of the optic fiber cable by a cable grip. This is a length of stainless steel braided wire terminated by an eye. As the tape is pulled, the tension increases and the braiding decreases in diameter, gripping the cable somewhat like a Chinese finger trap. The harder we pull, the tighter it gets. To reduce the friction experienced by the cable as it slides along the duct proprietary lubricants can be applied to the outside of the cable.

Blown fiber

This is an alternative technique available for distances up to about 2 km. It is unique in that it involves the installation of a cable empty of any optic fibers; these are added afterwards. This has three real advantages. It defers much of the cost since only the optic fibers actually required at the time need to be installed. It allows the system to be upgraded by the replacement of individual optic fibers and finally, as a bonus, the installation of the optic fiber is completely stress free.

The first step is to install the empty loose tube cable, which in itself is little more than an empty tube. The cable shown in Figure 8.10 contains seven tubes, each of 5 mm diameter in an outer jacket of 18 mm diameter. No commitment to use any particular number or types of fibers needs to be made at this stage in the proceedings.

Figure 8.10 Blown fiber tubing – no fiber installed



The next stage is to blow in the fibers. This can be done the same day as the tube (also known as MicroDuct) is installed or ten years later.

There are two methods available. One is to blow in a group of individual fibers, up to 12, into the tube and the second method is to blow in a bunch of fibers preformed into a simple bundle. In each case the fibers or bundle of fibers have a very special anti-static, low friction coating applied by the manufacturer.

The advantages of individual fibers are that they can cope with numerous tight bends better than a larger bundle and being presented as individual fibers at the termination point they can be organized and terminated quicker. The advantages of a fiber bundle are that the larger, stiffer unit can go longer distances and the blowing machine can be simpler than the multi-fiber version. Blown fiber ribbon is also possible as is fiber already preterminated at one end.

In every case the blowing machine simply feeds the fibers into the tube but it is the application of a supply of compressed air that provides the motive power to move the fibers along the duct.

A small compressor, called a blowing head, is attached to the end of the loose tube and blows air through it. The fiber is then fed in through the same nozzle as the air and is supported by the air stream. The fiber is blown along the tube and happily round bends in the duct, like a leaf in the wind, at a rate of about two meters a second, a goodish walking pace. No stress is felt by the fiber as it is supported by the movement of the air all along its length.

Other fibers can be blown in at any time to suit the customer although you can't add fiber to an already populated duct. However the fibers are equally easy to remove if the fiber needs to be upgraded at a future date.

A group of microducts is called a multiduct and a typical installation would have a 7-tube multiduct installed, which is potentially an 84 fiber cable, although only twelve might be installed in the first instance to give the network its connectivity required from day one. This leaves an upgrade path of at least 72 fibers available for the building or campus in the future.

To maintain the value of installed microducts they must be sealed to prevent the ingress of dirt, water and insects which would seriously hamper any future attempts to blow in fiber!

The manufacture of optic fiber

This is intended as a brief outline to the process offered, more out of interest than any pretense of it being useful.

There are several different methods in use today but the most widespread is called the modified chemical vapor deposition (MCVD) process.

At the risk of oversimplifying a complex process, we can summarize the process in three easy stages.

Stage 1 – Figure 8.11

A hollow silica tube is heated to about 1500°C and a mixture of oxygen and metal halide gases is passed through it. A chemical reaction occurs within the gas and a glass *soot* is formed and deposited on the inside of the tube. The tube is rotated while the heater is moved to and fro along the tube and the soot transforms a thin layer of silica glass. The rotation and heater movement ensures that the layer is of constant thickness. The first layer that is deposited forms the cladding and by changing the constituents of the incoming gas the refractive index can be modified to produce the core. Graded index fiber is produced by careful continuous control of the constituents.

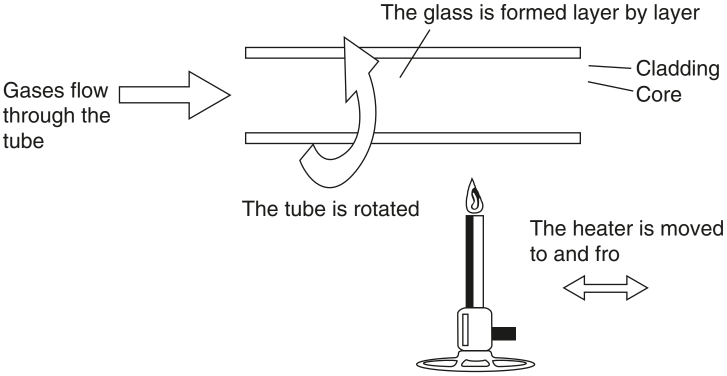


Figure 8.11 Stage 1 – the core and cladding are formed inside the tube

Stage 2 – Figure 8.12

The temperature is now increased to about 1800°C and the tube is collapsed to form a solid rod called a preform. The preform is about 25 mm in diameter and a meter in length. This will produce about 25 km of fiber.

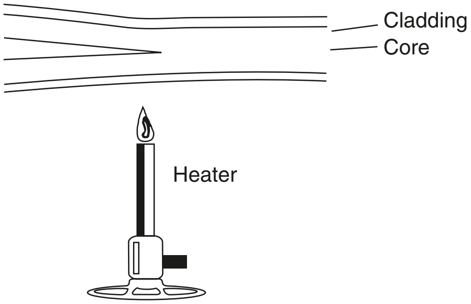


Figure 8.12 Stage 2 – further heating collapses the tube

Stage 3 – Figure 8.13

The preform is placed at the top of a high building called a pulling tower and its temperature is increased to about 2100°C. To prevent contamination, the atmosphere is kept dry and clean. The fiber is then pulled as a fine strand from the bottom, the core and cladding flowing towards the pulling point. Laser gauges continually monitor the thickness of the fiber and automatically adjust the pulling rate to maintain the required thickness. After sufficient cooling, the primary buffer is applied and the fiber is drummed.

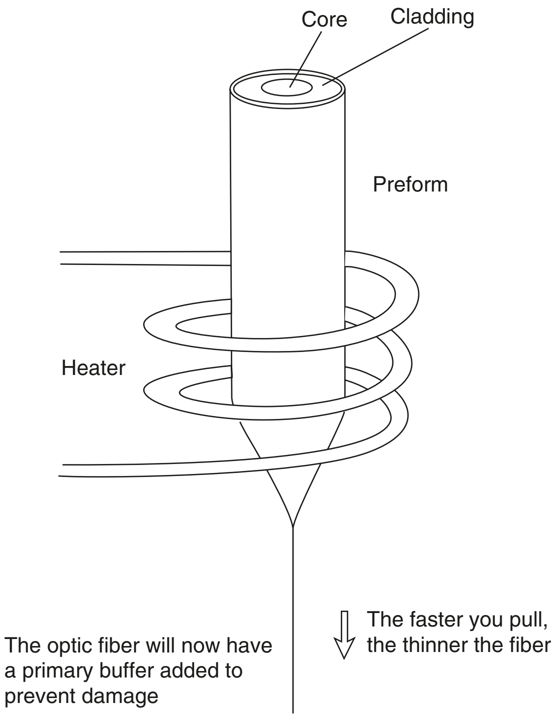
Advantages of optic fibers

The fact that optic fibers do not use copper conductors, and even the strength members need not be metallic, gives rise to many advantages.

Immunity from electrical interference

Optic fibers can run comfortably through areas of high level electrical noise such as near machinery and discharge lighting.

Figure 8.13
Stage 3 – the fiber is drawn



No crosstalk

When copper cables are placed side by side for a long distance, electromagnetic radiation from each cable can be picked up by the others and so the signals can be detected on surrounding conductors. This effect is called *crosstalk*. In a telephone circuit it results in being able to hear another conversation in the background. Crosstalk does not trouble optic fibers even if they are closely packed.

Glass fibers are insulators

Being an insulator, optic fibers are safe for use in high voltage areas. They will not cause any arcing and can be connected between devices which are at different electrical potentials, hence no earth loop currents.

The signals are carried by light and this offers some more advantages.

Improved bandwidths

Using light allows very high bandwidths. Bandwidths of several Gigahertz are available on fibers whereas copper cables are restricted to hundreds of Megahertz.

Security

As the optic fibers do not radiate electromagnetic signals, they offer a high degree of security as discussed in Chapter 6.

Low losses

Fibers are now available with losses as low as $0.2\,\mathrm{dB} \cdot \mathrm{km}^{-1}$ and hence very wide spacing is possible between repeaters. This has significant cost benefits in long distance telecommunication systems, particularly for undersea operations.

Size and weight

The primary coated fiber is extremely small and light, making many applications like endoscopes possible. Even when used as part of a cable with strength members and armoring, the result is still much lighter and smaller than the copper equivalents. This provides many knock-on benefits like reduced transport costs and also allowing more cables to be fitted within existing ducts.

Only a single fiber is required

One fiber can send a signal whereas copper requires two wires, one of which is needed as a return path to complete the electrical circuit.

Quiz time 8

In each case, choose the best option.

1 A cable containing both optic fiber and copper conductors is called:

(a) an armored cable
(b) a dehydrated cable
(c) tight-jacketed cable
(d) a hybrid cable

2 A white fiber with a black tracer is most likely to be fiber number:

(a) 18
(b) 16
(c) 14
(d) 12

3 Spiral galvanized wires are sometimes added to a cable to:

(a) conduct electricity
(b) allow the cable to stretch more to relieve stress
(c) improve crush resistance
(d) allow the fibers to be upgraded as necessary

4 Blown fiber allows:

(a) easy removal of the fibers to clean the ducts
(b) the diameter of the fiber to be increased by filling it with compressed air

(c) easy removal of any water in the fiber
(d) easy replacement of any damaged fiber

5 Within buildings:

(a) both tight-buffered and loose-jacketed cables are used
(b) only loose-jacketed cables are used
(c) only armored cables can be used
(d) only tight-buffered cables are used