CHAPTER 19

Public networks and the integrated services digital network (ISDN)

19.1 Introduction

This chapter examines how many of the techniques discussed earlier in the book are applied within the international public communications network. It covers the integrated services digital network (ISDN) [Griffiths], and includes discussion of the older plesiochronous, and newer synchronous, multiplexing techniques. The synchronous digital hierarchy (SDH) [Omidyar and Aldridge] is described, its frame structure and payload capacity defined, and its advantages outlined.

As much of this network now employs wideband fibre optic links, the principles and capabilities of fibre transmission, and optical pulse generation, reception and amplification, are summarised and a typical optical link budget presented. Finally this chapter concludes with a brief account of accessing schemes and on-going developments in the local loop network for digitised speech and data connections using primary, and basic, rate ISDN access.

19.2 The telephone network

The internationally agreed European ITU-T standard for PCM, TDM digital telephony multiplexing (Figure 5.27), is shown in Figure 19.1. Although this shows the basic access level at 144 kbit/s, the multiplexing hierarchy provides for the combining of 32 individual 64 kbit/s channels (Chapter 6) into a composite 2.048 Mbit/s signal. (In the USA the first level in the multiplex combines only 24 channels into a 1.544 Mbit/s data stream.) Multiplexing allocates a complete communications channel to each active user for the duration of his call or connection. In principle, as the channel utilisation factor for voice communications is low, we could concentrate the traffic by switching between users as they require transmission capacity. This resource saving strategy is not used in terrestial telephony but digital speech interpolation (DSI) is employed on international satellite circuits to achieve a significant increase in capacity, (see section 14.3.7).

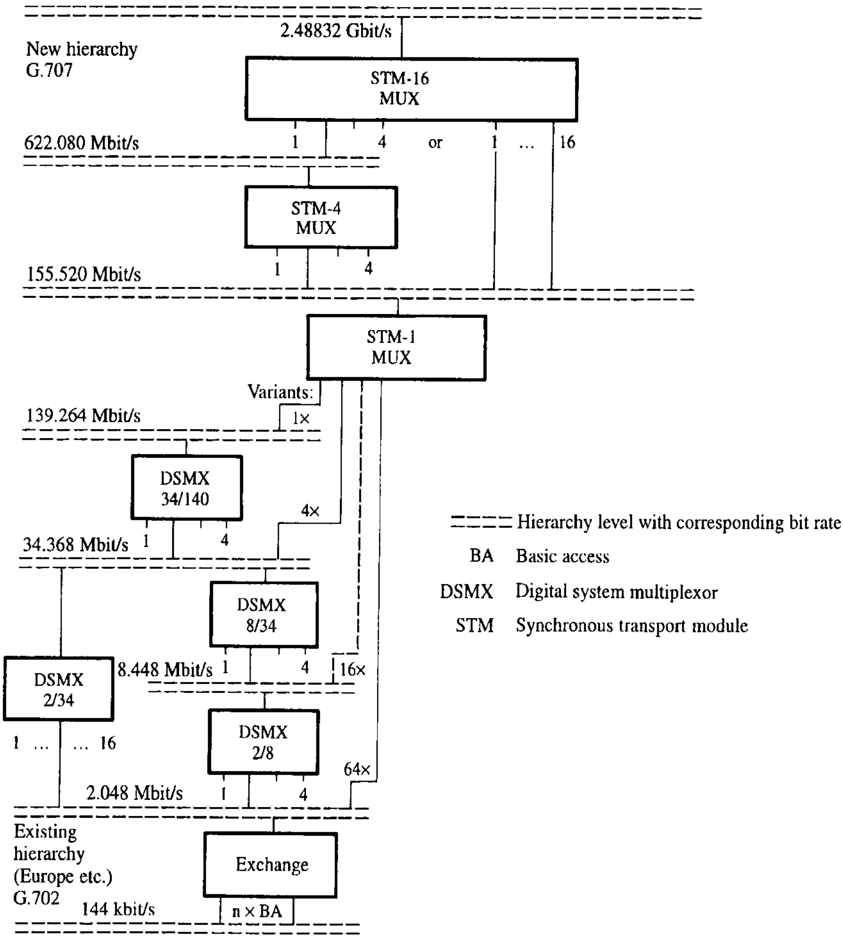


Figure 19.1 *ISDN access to European PCM TDM hierarchy with SDH at the upper levels.*

The ITU-T provides for higher levels of multiplexing, above 2.048 Mbit/s, combining four signals, in the digital system multiplexers (DSMX) 2/8 and 8/34, Figure 19.1, to form the signal at the higher multiplexing level. At each level the bit rate increases by slightly more than a factor of 4 since extra bits are added to provide for frame alignment and to facilitate satisfactory demultiplexing (see section 19.3). The upper levels, beyond 140 Mbit/s, form the synchronous digital hierarchy (SDH), and are only in limited use at present. These will be described later.

The extent of the current digital UK telephone network is shown in Figure 19.2. This is divided into an outer core of main processor exchanges and an inner core of about 55 trunk exchanges (digital main switching centres) which are fully interconnected on 140 Mbit/s, or higher bit rate, transmission links. These are now mainly optical links but also include coaxial, and terrestial microwave relay, paths. On 140 Mbit/s, 1.3 μm, optical fibre links, described later in section 19.5, the repeater spacing is typically 20 km while on microwave radio links, Chapter 14, the spacing is closer to 50 km. International access in Figure 19.2 is provided via satellite links or fibre-optic undersea cables.

Each subscriber telephone has two copper wires that go directly to the local exchange building, Figure 19.3. (The distance is typically 1 to 10 km, being smaller in cities than

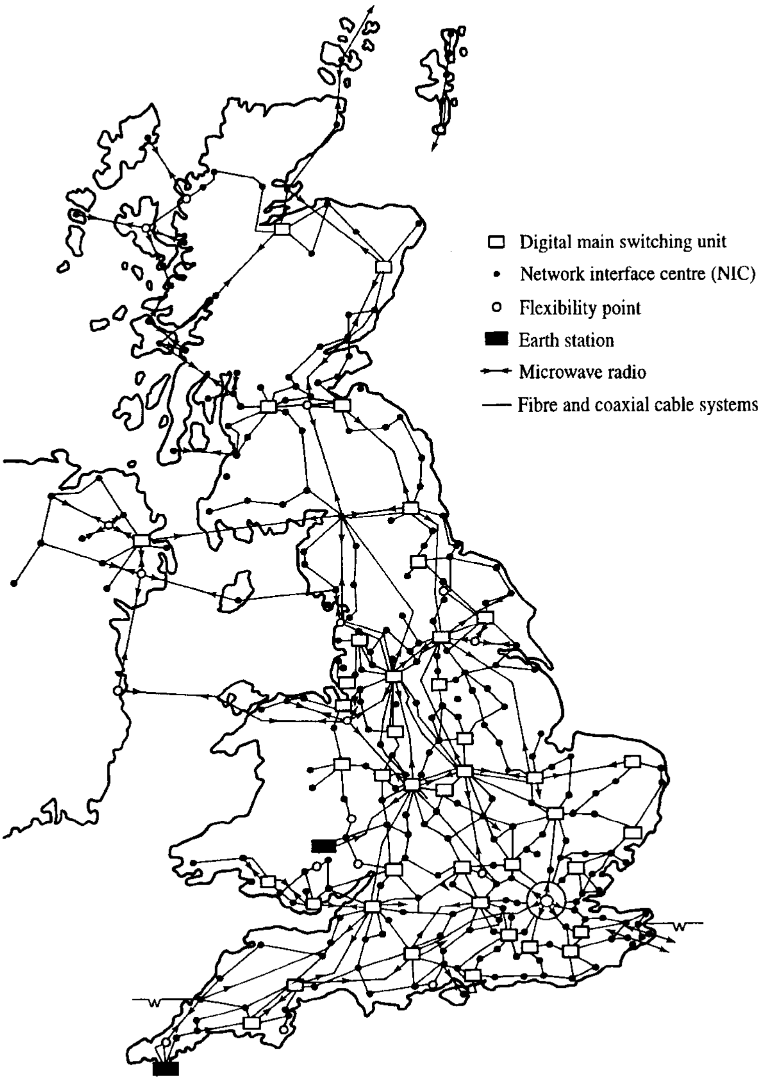


Figure 19.2 *ISDN locations and UK digital trunk telecommunications network (source: Leakey, 1991, reproduced with the permission of British Telecommunications plc.).*

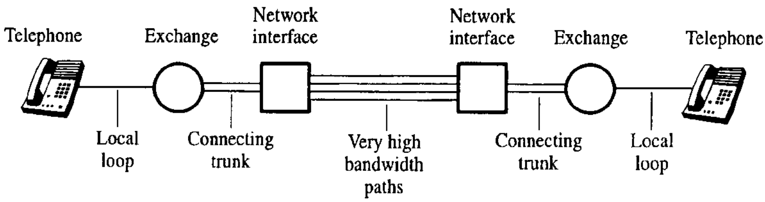


Figure 19.3 *Trunk telecommunications system used for establishing a connection.*

in rural areas where one exchange normally serves 40 km^2 or 5,000 to 50,000 customers.) The two-wire access connection between each subscriber's telephone and the exchange is known as the *local loop*. Each exchange has a number of outgoing lines to one or more nearby switching centres which provide the network interface. Figure 19.3 shows the typical connection for a long distance (trunk) call involving both inner and outer core connections. In this system there are four wires to the microphone and speaker in the handset, two wires in the local loop and four wires again in the national trunk network. (A four wire circuit implies separate transmit and receive channels as in cellular radio systems, Chapter 15.) In the UK there are approximately 6300 local exchange buildings and the local access network comprises 36 million metallic pair cables.

Traditional control signalling in circuit-switched telephone networks for establishing or initiating call connections may either use a separate communications channel or operate on an in-channel basis. With in-channel signalling, the same channel is used to carry control signals as is used to carry message traffic. Such signalling begins at the originating subscriber and follows the same path as the call itself. This has the merit that no additional transmission facilities are needed for signalling. Two forms of in-channel signalling are in use, in-band and out-of-band. In-band signalling uses not only the same physical path as the call it serves, it also uses the same frequency band as the voice signals that are carried. Out-of-band signalling takes advantage of the fact that voice signals do not use the full 4 kHz of available bandwidth. A separate narrow signalling band, within the 4 kHz, is used to send control signals. A drawback of in-channel signalling schemes is the relatively long delay from the time that a subscriber dials a number to the connection being made.

This problem is addressed by common channel signalling in which control signals are carried by an independent signalling network. Since the control signal bandwidth is small, one separate control signal path can carry the signals for a number of subscriber channels. The common channel uses a signalling protocol, and requires the network architecture to support that protocol, which is more complex than the in-channel signalling case. The control signals are messages that are passed between switches and between a switch and the network management centre.

Over the past decade several different general purpose signalling systems have been developed by ITU and other standards organisations. The most important of these, and the one of major relevance to the ISDN, is the set of procedures known as signalling system No. 7, which is structured in accordance with the ISO OSI model of Figure 18.12. The overall objective is to provide an internationally standardised, general purpose, common channel signalling system which:

- is optimised for use in digital telecommunication networks in conjunction with digital stored program control exchanges utilising 64 kbit/s digital signals;
- is designed to meet present and future information transfer requirements for call control, remote network management, and maintenance;
- provides a reliable means for the transfer of information packets in the correct sequence without loss or duplication;
- is suitable for use on point-to-point terrestrial and satellite links.

19.3 Plesiochronous multiplex

The 2.048 Mbit/s multiplex level (also called the PCM primary multiplex group) in Figures 19.1 and 19.4 comprises frames with 32 8-bit time slots within each frame, Figure 19.5. Time slot zero is reserved for frame alignment and service bits, and time slot 16 is used for multiframe alignment, service bits and signalling. The remaining 30 channels are used for information carrying, or payload capacity, each channel containing one 8-bit voice signal sample.

The system for assembling the TDM telephony data stream assumes that the digital multiplexers (DSMX) in Figure 19.4 are located at physically separate sites which implies separate free running oscillators at each stage in the multiplex hierarchy, hence the name plesiochronous. These oscillators must therefore run at speeds slightly higher than the incoming data, Figure 19.4, to permit local variations to be accommodated. This allows for small errors in the exact data rates in each of the input paths or tributaries but requires some extra bits to be added (i.e. stuffed or justified) to take account of the higher speed oscillator. Elastic stores, Figure 19.6, are used in a typical multiplexer to ensure sufficient bits are always available for transmission or reception. These stores are required because the plesiochronous digital hierarchy (PDH) works by interleaving bytes

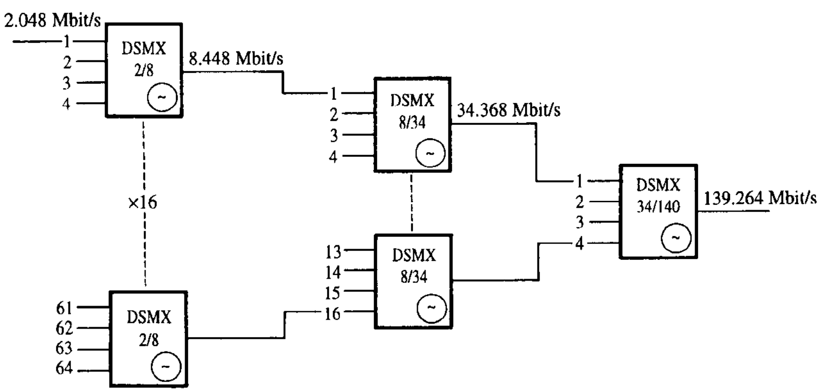


Figure 19.4 *DSMX interconnection to form a plesiochronous multiplex hierarchy.*

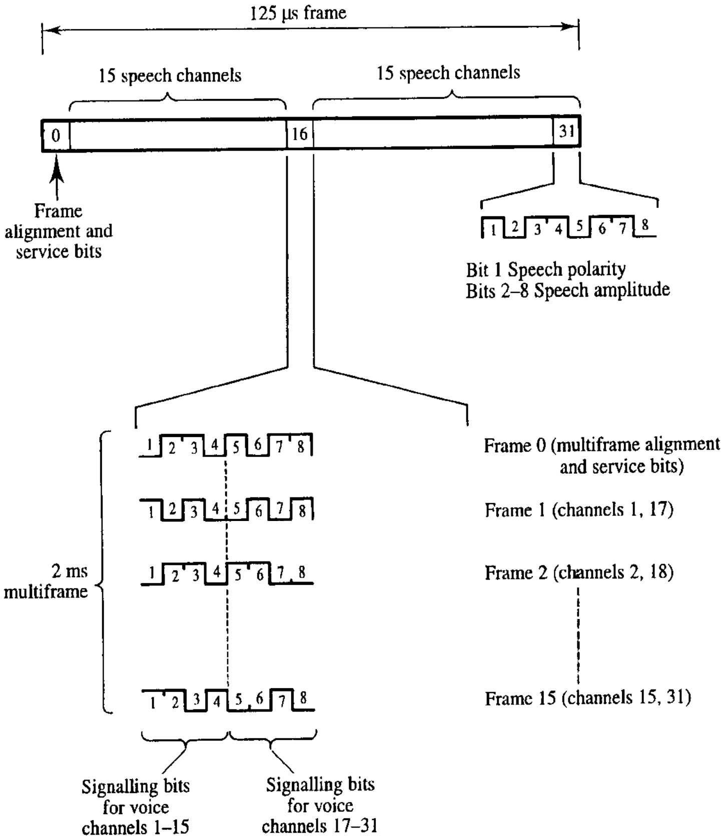


Figure 19.5 *PCM primary multiplex group frame structure.*

or words from each 64 kbit/s tributary, rather than bit interleaving, to form the 2 Mbit/s multiplex. Thus, at the 8 Mbit/s multiplexing level, and above, where bit interleaving is employed, bits must be accumulated for high speed readout.

Figure 19.7 shows more detail of the multiplexer hardware. The code translators in Figure 19.6 convert binary data from, and to, HDB3 (see section 6.4.5). Figure 19.8 shows details of the plesiochronous frame structure at 8 Mbit/s. (Note the bit interleaving, shown explicitly for the justification bits, used at multiplexing levels above 2 Mbit/s.) The ITU-T G series of recommendations (G.702) defines the complete plesiochronous multiplex hierarchy. The frame alignment signal, which is a unique word recognised in the receiver, ensures that the appropriate input tributary is connected to the correct output port. The unique word also permits receiver recovery from loss of synchronisation, if it occurs. The plesiochronous multiplex system was developed at a time when transmission costs were low and switching costs were high. With recent advances in VLSI this premise is now no longer valid, hence the movement to new standards.

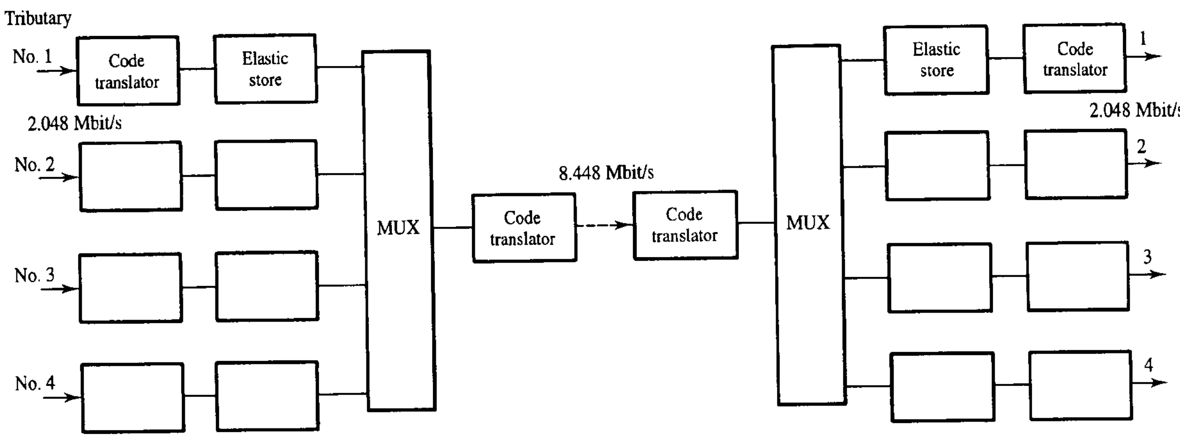


Figure 19.6 *2/8 Multiplexer block diagram.*

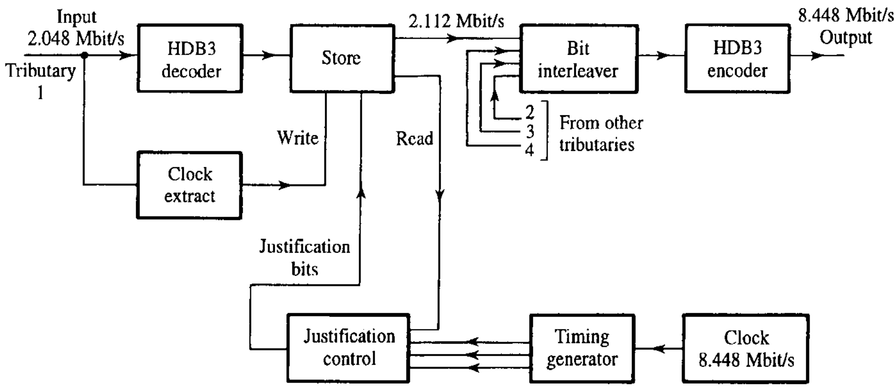


Figure 19.7 *2/8 multiplexer timing details.*

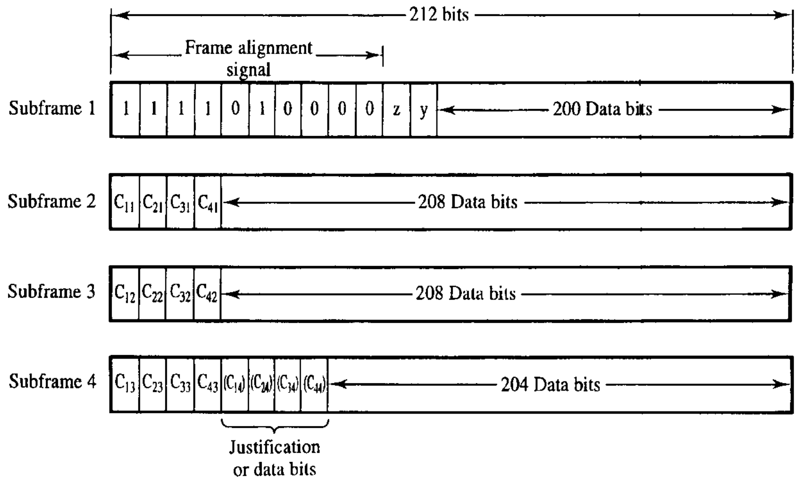


Figure 19.8 *Plesiochronous frame structure.*

A disadvantage of the plesiochronous multiplex is that it was designed for point-to-point transmission applications in which the entire multiplex would be decoded at each end. This is a complicated process since it requires full demultiplexing at each level to recover the bit interleaved data and remove the justification bits. Thus a single 2 Mbit/s channel, for example, cannot be extracted from, or added to, a higher level multiplex signal without demultiplexing down, and then remultiplexing up, through the entire PDH, Figure 19.9. The plesiochronous multiplex does *not* support definitive or clear identification of the various individual channels which are being carried.

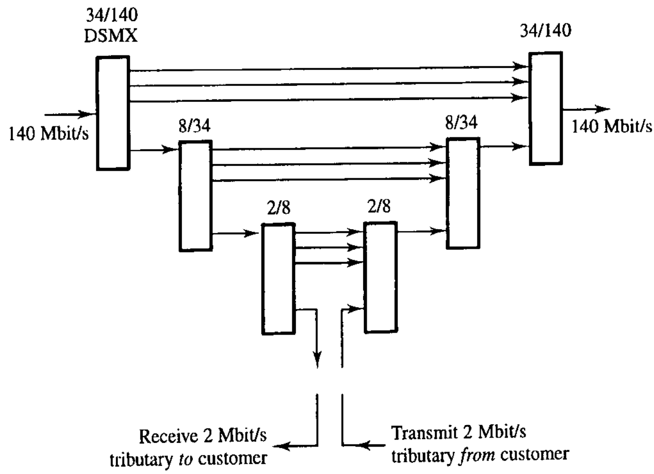


Figure 19.9 *Plesiochronous multiplex add-drop scheme for inserting, and removing, a 2 Mbit/s tributary to, and from, a 140 Mbit/s stream.*

Many high capacity transmission networks are provided by a hierarchy of digital plesiochronous signals. The plesiochronous approach to signal multiplexing is severely limited, however, in its ability to meet the foreseeable requirements of network operators. It does not provide, cost-effectively, the flexible network architecture which is required to respond to the demands of today's evolving telecommunications market. Furthermore, since network management and maintenance strategies were based, historically, on the availability of a manual distribution frame, there was no need to add extra capacity to the plesiochronous frame structure in order to support network operations, administration, maintenance and provisioning (OAM&P) activities. Other PDH drawbacks are the lack of a standard above 140 Mbit/s and the use of different plesiochronous hierarchies in different parts of the world. This leads to problems of interworking between countries whose networks are based on 1.544 Mbit/s (e.g. Japan, North America) and those basing their networks on 2.048 Mbit/s (e.g. Europe, Australia).

The PDH limitations described above, and the desire to move from metallic cable to wideband optical fibres, have been important motivations in the development of the new SONET and synchronous digital hierarchy (SDH) systems which are described in the following sections. These new systems offer improved flexibility and can more readily provide the 2 Mbit/s leased lines which, for example, cellular telephone operators require to connect their base station transmitters to switching centres. (Just prior to the move away from PDH towards SDH systems British Telecom (BT) did develop, in the 1980s, a single 64-channel 2 to 140 Mbit/s multiplexer. This has been included in Figure 19.1 as an input to the new 155.52 Mbit/s standard multiplexer rate.)

EXAMPLE 19.1
Find the number of standard PCM voice signals which can be carried by a PDH level 4 multiplex and estimate the maximum channel utilisation efficiency at this multiplexing level.

PDH Level 1 (primary multiplex group) carries 30 voice signals. Each subsequent level combines four tributaries from previous levels. At level n the number of potential voice signals is therefore given by:

$$\chi = 30 \times 4^{n-1}$$

At level four:

$$\chi = 30 \times 4^{4-1} = 1920 \text{ voice signals}$$

Nominal bit rate at PDH level 4 is 140 Mbit/s. Therefore channel utilisation efficiency is:

$$\eta_{ch} = \frac{\chi}{R_b/R_v} = \frac{1920}{(140 \times 10^6)/(64 \times 10^3)} = 88\%$$

19.4 SONET and SDH

The concept of the digital SONET (synchronous optical network) was initially introduced in the USA in 1986 to establish wideband transmission standards so that international operators could interface using standard frame formats and signalling protocols. The concept also included network flexibility and intelligence, and overhead channels to carry control and performance information between network elements (line systems, multiplexers) and control centres.

In 1988 these concepts were adopted by ITU and ETSI (European Telecommunications Standards Institute) and renamed synchronous digital hierarchy (SDH) with the aim of agreeing worldwide standards for transmission covering optical interfaces, control aspects, equipment, signalling, etc. [Miki and Siller]. Bit transport rates start as low as 52 Mbit/s and go up through 155 Mbit/s with a hierarchy to 622 Mbit/s, 2488 Mbit/s and beyond. The ITU-T G.707/8/9 standards have now reached a mature stage allowing manufacturers to produce common hardware.

19.4.1 Advantages and flexibility

The key advantages of SDH are as follows:

- it is cheaper to add and drop signals to meet customer requirements.
- more bandwidth is available for network management.
- equipment is smaller and cheaper.
- worldwide standards allow a larger manufacturers' marketplace.

- it is easier to introduce new services.
- it is cheaper to achieve remote digital access to services and cross-connections between transmission systems.

Network flexibility implies the ability to rapidly reconfigure networks from a control centre in order to:

- improve capacity utilisation by maximising the number of 2 Mbit/s channels transported in the higher order system;
- improve availability of digital paths by centrally allocating spare capacity and protection schemes to meet service requirements;
- reduce maintenance costs by diverting traffic away from failed network elements;
- provide easier growth with temporary diversion of traffic around areas being upgraded.

Flexibility can be achieved using automatic cross-connect switches between SDH systems or between SDH and plesiochronous systems. Automatic cross-connects will gradually replace existing manual cross-connects and allow remote reconfiguration of capacity within the network at 2 Mbit/s and above. Add-drop multiplexing refers to the ability to extract or insert individual channels without the need to demultiplex the entire high order signal, as required in the plesiochronous system.

19.4.2 Synchronous signal structure

The synchronous signal comprises a set of 8-bit bytes which are carefully interleaved into a frame structure such that the identity of each byte is preserved and known with respect to a framing (or marker) word. The description of the synchronous signal frame structure used here is one in which the bytes of the signal are represented by boxes appearing in rows and columns on a 2-dimensional map, Figure 19.10 [Hawker]. (This is not unlike the masterframe structure of Figure 14.43.)

The signal bits are transmitted in a raster scanned sequence, similar to the lines on a video signal, starting with those in the top left hand byte, followed by those in the 2nd byte in row 1, and so on, until the bits in the *M*th (last) byte in row 1 are transmitted. Then the bits in the 1st byte of row 2 are transmitted, followed by the bits in the 2nd byte of row 2, and so on, until the bits in the *M*th byte of the *N*th (last) row are transmitted.

This transmission sequence repeats, the repetition rate being 8000 frame/s. The duration of each frame is, therefore, 125 μs and the bit rate associated with each byte in the frame is 8×8 kbit/s = 64 kbit/s. Each byte in the frame is thus equivalent in capacity to one PCM voice channel. One or more 8-bit bytes within the synchronous signal structure may be allocated to provide channel capacity for a lower rate (tributary) signal. The fixed sequence frame alignment word allows the positions of all individual data streams within the frame to be identified.

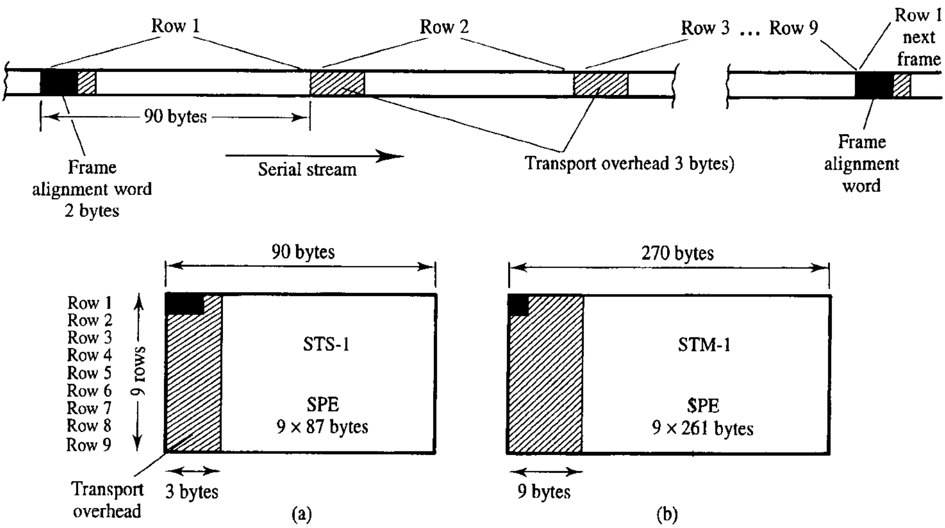


Figure 19.10 *Frame structures showing serial bit stream (for SONET) and the equivalent two dimensional data maps: (a) basic SONET STS-1 frame; and (b) SDH STM-1 frame.*

19.4.3 Frame structure

The lowest level SONET signal is called the synchronous transport signal level 1 (STS-1). It consists of 90 columns and 9 rows of 8-bit bytes giving a total 810 bytes (6480 bits), Figure 19.10(a). With a frame duration of 125 μs, the STS-1 bit rate is 51.84 Mbit/s. The basic SDH frame corresponds to three SONET STS-1 frames and is called a level 1 synchronous transport module (STM-1), Figure 19.10(b). The STM-1 bit rate is therefore 155.52 Mbit/s. Each STS-1 frame can be seen to comprise two parts – an overhead part and a service payload part.

Transport overhead: The first three columns of the STS-1 frame, a total of 27 bytes, Figure 19.10(a), are allocated to overheads that provide operations and maintenance (O&M) facilities. The three bytes in rows 1, 2 and 3 comprise the section overhead while the remaining three bytes in rows 4 to 9 (18 bytes) comprise the line overhead. The section and line terminology is defined in Figure 19.11 for a communications link. (Line terminating equipment might be represented, for example, by an add-drop multiplexer.)

Synchronous payload envelope (SPE): The remaining 87 columns of the STS-1 frame, a total of 783 bytes, provide a channel capacity of 50.112 Mbit/s which supports the transport of the service payload, or traffic data, and also the path overhead, Figure 19.12.

Path overhead: The path overhead supports and maintains the transportation of the SPE between the locations where the SPE is assembled and disassembled. It comprises a total of 9 bytes, Figure 19.12, and is allocated the first column (one byte wide) within the STS-1 SPE.

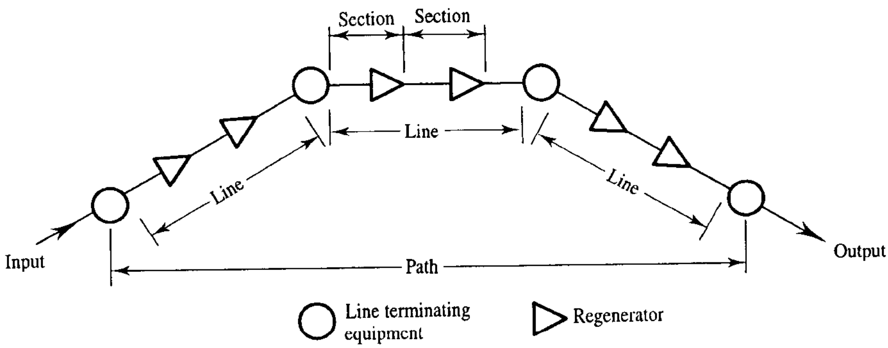


Figure 19.11 *Path, line and section details in a communications link.*

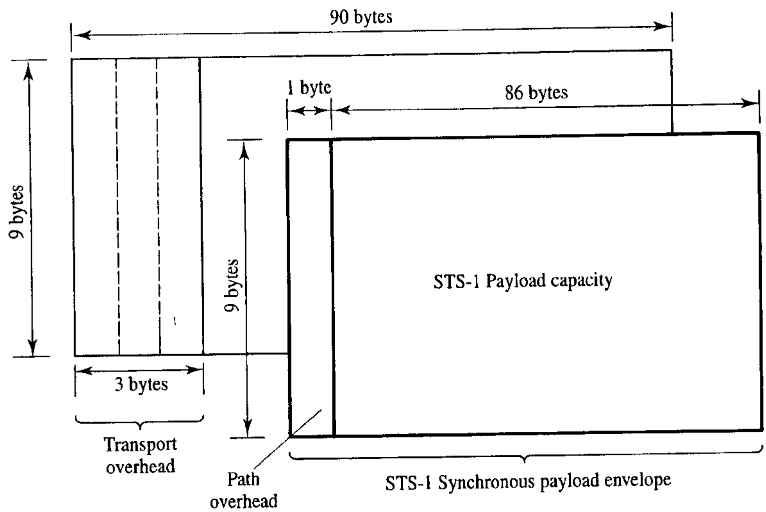


Figure 19.12 *STS-1 synchronous payload envelope (SPE).*

Payload capacity: The STS-1 information capacity comprises the remaining 86 columns of 9 bytes, i.e. a total of 774 bytes providing a 49.536 Mbit/s channel capacity with a frame repetition rate of 8 kHz.

The SONET/SDH frame structure features greatly simplified 'drop and insert' and cross-connect functions by utilising:

- a modular structure made up from SONET/SDH tributaries;
- extensive overheads for monitoring and control;
- byte interleaving with direct visibility of 64 kbit/s channels;
- byte stuffing to improve robustness against loss of synchronisation;

- standard mappings for all common data rates into the SONET/SDH frame format.

The STS-1 SPE represents the unshaded part of Figure 19.10(a). Additional transport capacity is obtained by effectively concatenating SPEs, Figure 19.10(b). Alternatively a reduction in transport capacity may be obtained by partitioning the SPE into smaller segments, called virtual tributaries or VTs (see section 19.4.5).

19.4.4 Payload pointer

To facilitate efficient multiplexing and cross-connection of signals in the synchronous network, the SPE is allowed to 'float' within the payload capacity provided by the STS-1 frames, Figure 19.13. This means that the STS-1 SPE may begin anywhere in the STS-1 frame and is unlikely to be wholly contained in one frame. More likely than not, the STS-1 SPE will begin in one frame and end in the next.

The STS-1 payload pointer, contained in the transport overhead, indicates the location of the first byte of the STS-1 SPE. Byte 1 of the STS-1 SPE is also the first byte of the SPE path overhead. It permits non-synchronous data to be accommodated within the SDH structure, without resorting to justification or bit stuffing.

For synchronous transport, payload pointers provide a means of allowing an SPE to be transferred between network nodes operating plesiochronously. Since the SPE floats freely within the transport frame, with the payload pointer value indicating the location of the first active byte of the SPE, the problem in justified plesiochronous multiplex where the traffic is mixed with stuffing bits is overcome.

Payload pointer processing does, however, introduce a new signal impairment known as 'tributary jitter'. This appears on a received tributary signal after recovery from a synchronous payload envelope which has been subjected to payload pointer movements from frame-to-frame. Excessive tributary jitter will influence the operation of the downstream plesiochronous network equipment processing the tributary signal.

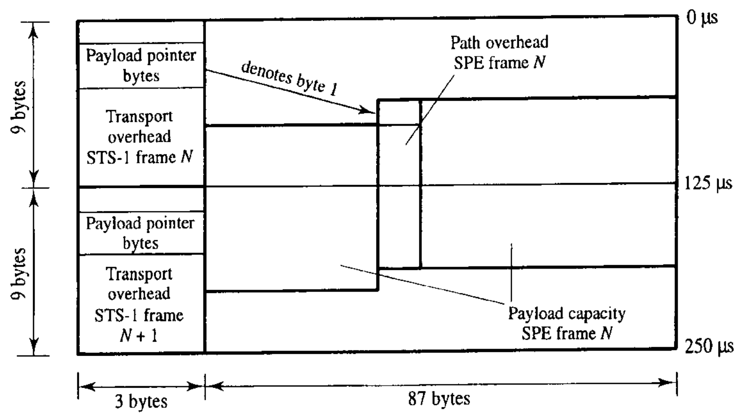


Figure 19.13 *Payload pointer details for locating the start of the SPE.*

19.4.5 Payload capacity partitioning

The virtual tributary (VT) structure (or tributary unit structure in SDH terminology) has been designed to support the transport and switching of payload capacity which is less than that provided by the full STS-1 SPE. There are three sizes of VTs in common use, Figure 19.14. These are:

- VT1.5, consisting of 27 bytes, structured as 3 columns of 9, which, at a frame rate of 8 kHz, provides a transport capacity of 1.728 Mbit/s and will accommodate a US 1.544 Mbit/s DS1 signal.
- VT2, consisting of 36 bytes, structured as 4 columns of 9, which provides a transport capacity of 2.304 Mbit/s and will accommodate a European 2.048 Mbit/s signal.
- VT3, consisting of 54 bytes, structured as 6 columns of 9, to achieve a transport capacity of 3.456 Mbit/s which will accommodate a US DS1C signal.

These and other VTs allow the SDH structure to be electronically reconfigured on demand to handle different customer requirements. It circumvents the fixed nature of the plesiochronous multiplex and, as the VTs are distributed over the entire payload, they can be easily written to, and read from, the system without requiring large data buffer stores.

A 155.52 Mbit/s SDH transmission capability is obtained by combining three STS-1 SPEs into one STM-1 SPE, Figure 19.10(b). Higher order systems are formed by byte interleaving $N \times 155$ Mbit/s channels (e.g. 16×155.5 Mbit/s = 2488 Mbit/s) to form the synchronous transport module level N (e.g. STM-16) rate, Figure 19.1. The SDH frame format allows simultaneous transport of both narrowband (e.g. 2 Mbit/s) and broadband (e.g. 45/140 Mbit/s) services within the 155 Mbit/s capacity system.

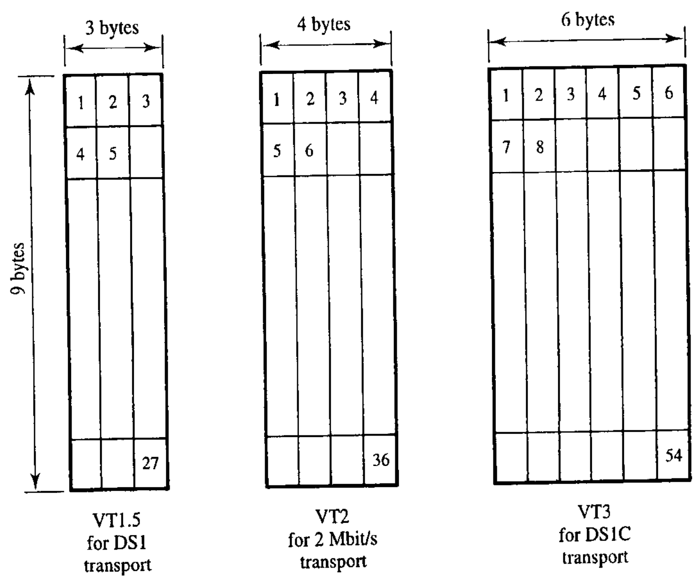


Figure 19.14 *Virtual tributaries of the STS-1 frame.*

EXAMPLE 19.2

Estimate the number of voice channels which can be accommodated by an SDH STM-4 signal assuming that the STM-4 is filled with ITU primary multiplex group signals. Also estimate the channel utilisation efficiency.

Each STS-1 payload envelope has 86 columns (not including the path overhead column). Each primary multiplex group occupies 4 columns. Each STS-1 payload envelope can therefore transport 86/4 = 21 (whole) primary multiplexes.

Each STM-1 payload envelope corresponds to 3 STS-1 payload envelopes and therefore carries $3 \times 21 = 63$ primary multiplexes. STM-4 carries 4 STM-1 signals and therefore carries $4 \times 63 = 252$ primary multiplexes. Each primary multiplex carries 30 voice channels, Figure 19.5. The STM-4 signal can, therefore, carry $30 \times 252 = 7560$ voice channels.

Channel utilisation efficiency, η_{ch}, is thus given by:

$$\eta_{ch} = \frac{7560}{R_b/R_v} = \frac{7560}{(622.08 \times 10^6)/(64 \times 10^3)}$$

$$= \frac{7560}{9720} = 78\%$$

19.5 Fibre optic transmission links

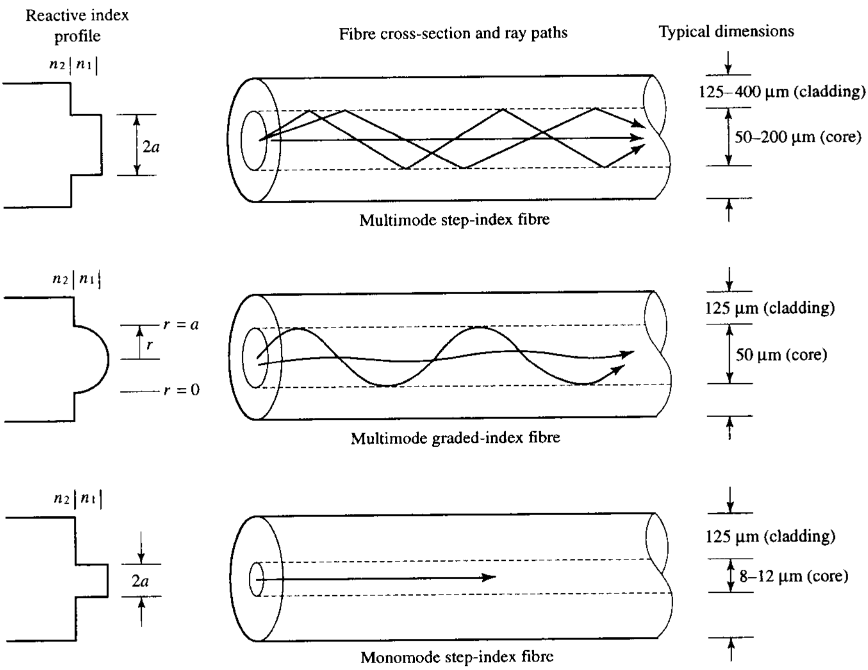
Optical fibres comprise a core, cladding and protective cover and are much lighter than metallic cables [Gowar]. This advantage, coupled with the rapid reduction in propagation loss to its current value of 0.2 dB/km or less, Figure 1.6(e), and the enormous potential bandwidth available, make optical fibre now the only serious contender for the majority of long-haul trunk transmission links. The potential capacity of optical fibres is such that all the radar, navigation and communication signals in the microwave and millimetre wave region, which now exist as free space signals, could be accommodated within 1% of the potential operational bandwidth of a single fibre. Current commercial systems can accommodate 31,000 simultaneous telephone calls in a single fibre and 1M call capacity has been achieved in the laboratory.

19.5.1 Fibre types

In the fibre a circular core of refractive index n_1 is surrounded by a cladding layer of refractive index n_2, where $n_2 < n_1$, Figure 19.15. This results in optical energy being guided along the core with minimal losses.

The size of the core and the nature of the refractive index change from n_1 to n_2 determine the three basic types of optical fibre [Gowar], namely:

- multimode step-index;
- multimode graded-index;



Digital Communications Fig 19.15

- monomode step-index.

The refractive index profiles, typical core and cladding layer diameters and a schematic ray diagram representing the distinct optical modes in these three fibre types are shown in Figure 19.15. The optical wave propagates down the fibre via reflections at the refractive index boundary or refraction in the core. In multimode fibres there was, originally, a 20% difference between the refractive indices of the core and the cladding. In the more recently developed monomode fibres, the difference is much smaller, typically 0.5%. The early multimode step index fibres were cheap to fabricate but they had limited bandwidth and a limited section length between repeaters. In a 1 km length of modern multimode fibre with a 1% difference in refractive index between core and cladding, pulse broadening or dispersion, caused by the difference in propagation velocity between the different electromagnetic modes, limits the maximum data rate to, typically, 10 Mbit/s. Graded index fibres suffer less from mode dispersion because the ray paths representing differing modes encounter material with differing refractive index. Since propagation velocity is higher in material with lower refractive index, the propagation delay for all the modes can, with careful design of the graded-*n* profile, be made approximately the same. For obvious reasons *modal* dispersion is absent from monomode fibres altogether and in these fibre types *material* dispersion is normally the dominant pulse spreading mechanism. Material dispersion occurs because refractive index is, generally, a function of wavelength, and different frequency components therefore propagate with different velocities. (Material dispersion is exacerbated due to the fact that practical sources often emit light with a narrow, but not monochromatic, spectrum.) The rate of change of propagation velocity with frequency (dv/df), and therefore dispersion, in silica fibres changes sign at around 1.3 μm, Figure 19.16, resulting in zero material dispersion at this wavelength. (Fortuitously, this wavelength also corresponds to a local minimum in optical attenuation, see Figure 1.6(e).)

If both modal and material dispersion are zero, or very small, *waveguide* dispersion, which is generally the weakest of the dispersion mechanisms, may become significant. Waveguide dispersion arises because the velocity of a waveguide mode depends on the normalised dimensions (d/λ) of the waveguide supporting it. Since the different frequency components in the transmitted pulse have different wavelengths these components will travel at different velocities even though they exist as the same electromagnetic mode. Because both material and waveguide dispersion relate to changes in propagation velocity with wavelength they are sometimes referred to collectively as chromatic dispersion. The various fibre types are further defined in ITU-T recommendation G.652.

19.5.2 Fibre transmission systems

There have been three generations of optical fibre systems operating at 0.85 μm, 1.3 μm and 1.5 μm wavelengths to progressively exploit lower optical attenuation, Figure 1.6(e), and permit longer distances to be achieved between repeaters. Monomode fibres, with core diameters in the range 8 to 12 μm, have been designed at the two longer wavelengths for second and third generation systems. Since material dispersion is zero at around 1.3

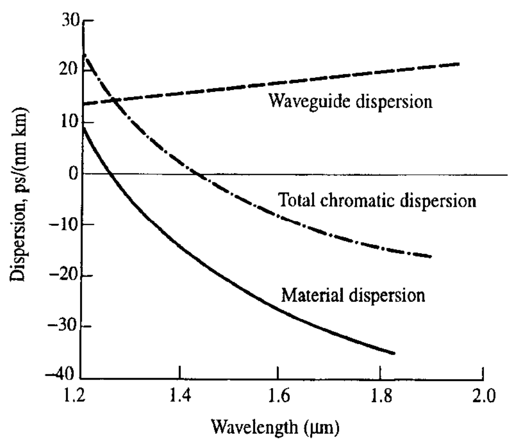


Figure 19.16 *Variation of material dispersion and waveguide dispersion, giving zero total dispersion near λ = 1.5 μm (source, Flood and Cochrane, 1989, reproduced with the permission of Peter Peregrinus).*

μm, where the optical attenuation in silica is also a local minimum, this was the wavelength chosen for second generation systems, which typically operate at 280 Mbit/s.

Third generation systems operate at wavelengths around 1.5 μm and bit rates of 622 Mbit/s to exploit the lowest optical attenuation value of 0.15 dB/km, and tolerate the resulting increased chromatic dispersion which in practice may be 15 to 20 ps $nm^{-1}km^{-1}$. Thus, the choice at present between 1.3 and 1.5 μm wavelength depends on whether one wants to maximise link repeater spacing or signalling bandwidth.

Figure 19.16 shows that if core dimensions, and core cladding refractive indices, are chosen correctly, however, material dispersion can be cancelled by waveguide dispersion at about 1.5 μm resulting in very low total chromatic dispersion in this lowest attenuation band.

The impact of fibre developments is clearly seen in Figures 1.7 and 19.17. The latter illustrates the evolution of transmission technology for a 100 km wideband link. The coaxial cable used in the 1970s with its associated 50 repeaters had a mean time between failures (MTBF) of 0.4 years, which was much lower than the 2 year MTBF of the plesiochronous multiplex equipment at each terminal station. Multi-mode fibre (MMF) still needed a repeater every 2 km but was a more reliable transmission medium. The real breakthrough came with single mode fibre (SMF) and, with the low optical attenuation at 1.5 μm, there is now no need for any repeaters on a 100 km link, in which the fibre path loss is typically 10 to 28 dB. (This is *very* much lower than the microwave systems of section 12.4.2.) By 1991 there were 1.5 million km of installed optical fibre carrying 80% of the UK telephone traffic. This UK investment represented 20% of the world transmission capability installed in optical fibre at that time. Optical fibre transmission capacity doubles each year with an exponentially reducing cost.

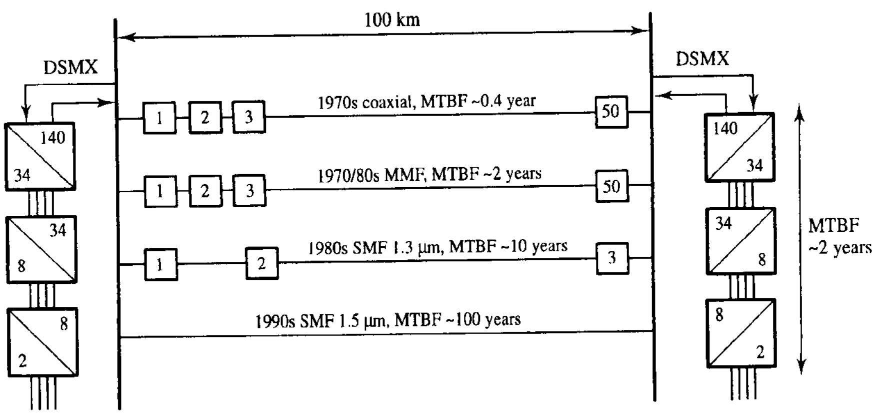


Figure 19.17 *Evolution of a 100 km link from coaxial to optical transmission (source: Cochrane, 1990, reproduced with the permission of British Telecommunications plc.).*

19.5.3 Optical sources

Two devices are commonly used to generate light for fibre optic communications systems: light-emitting diodes (LEDs) and injection laser diodes (ILDs). The edge emitting LED is a PN junction diode made from a semiconductor material such as aluminium–gallium–arsenide (AlGaAs) or gallium–arsenide–phosphide (GaAsP). The wavelength of light emitted is typically 0.94 μm and output power is approximately 3 mW at 100 mA of forward diode current. The primary disadvantage of this type of LED is the non-directionality of its light emission which makes it a poor choice as a light source for fibre optic systems. The planar hetero-junction LED generates a more brilliant light spot which is easier to couple into the fibre. It can also be switched at higher speeds to accommodate wider signal bandwidth.

The injection laser diode (ILD) is similar to the LED but, above the threshold current, an ILD oscillates and lasing occurs. The construction of the ILD is similar to that of an LED, except that the ends are highly polished. The mirror-like ends trap photons in the active region which, as they are reflected back and forth, stimulate free electrons to recombine with holes at a higher-than-normal energy level to achieve the lasing process. ILDs are particularly effective because the optical radiation is easy to couple into the fibre. Also the ILD is powerful, typically giving 10 dB more output power than the equivalent LED, thus permitting operation over longer distances. Finally, ILDs generate close to monochromatic light, which is especially desirable for single mode fibres operating at high bit rates.

19.5.4 Optical detectors

There are two devices that are commonly used to detect light energy in fibre optic systems: PIN (positive–intrinsic–negative) diodes and APDs (avalanche photodiodes). In the PIN diode, the most common device, light falls on the intrinsic material and photons are absorbed by electrons, generating electron-hole pairs which are swept out of the device by the applied electric field. The APD is a positive–intrinsic–positive–negative structure, which operates just below its avalanche breakdown voltage to achieve an internal gain. Consequently, APDs are more sensitive than PIN diodes, each photon typically producing 100 electrons, their outputs therefore requiring less additional amplification.

19.5.5 Optical amplifiers

In many optical systems it is necessary to amplify the light signal to compensate for fibre losses. Light can be detected, converted to an electrical signal and then amplified conventionally before remodulating the semiconductor source for the next stage of the communications link. Optical amplifiers, based on semiconductor or fibre elements employing both linear and non-linear devices, are much more attractive and reliable; they permit a range of optical signals (at different wavelengths) to be amplified simultaneously and are especially significant for sub-marine cable systems.

Basic travelling wave semiconductor laser amplifier (TWSLA) gains are typically in the range 10 to 15 dB, Figure 19.18. These Fabry-Perot lasers are multimode in operation and are used in medium distance systems. Single mode operation is possible with distributed feedback (DFB) lasers for longer distance, high bit rate, systems. In common with all optical amplifiers, the TWSLA generates spontaneous emissions which results in an optical (noise) output in the absence of an input signal. For a system with cascaded TWSLAs these noise terms can accumulate.

Recent research has resulted in fibre amplifiers consisting of 10 m to 50 km of doped or undoped fibre. These amplifiers use either a linear, rare earth (erbium), doping mechanism or the non-linear Raman/Brillouin mechanism [Cochrane *et al.* 1990]. The erbium doped fibre amplifier (EDFA) uses a relatively short section (1 to 100 m) of silica fibre pumped with optical, rather than electrical, energy. Because of the efficient coupling of fibre-to-fibre splices, high gains (20 dB) are achievable, Figure 19.18, over a 30 to 50 nm optical bandwidth. Practical amplifier designs generally have gains of 10 to 15 dB. The key attraction of this amplifier is the excellent end-to-end link SNR which is achievable and the enormous 4 to 7 THz (Hz $\times 10^{12}$) of optical bandwidth. (This far exceeds the 300 GHz of the entire radio, microwave and millimeter-wave spectrum.) Two interesting features of these amplifiers are the precise definition of the operating wavelength via the erbium doping and their relative immunity to signal dependent effects. They can therefore be engineered to maintain wide bandwidths when cascaded, and can operate equally well with OOK, FSK or PSK signals.

Injecting a high power laser beam into an optical fibre results in Raman scattering. Introducing a lower intensity signal-bearing beam into the same fibre with the pump energy, results in its amplification with gains of approximately 15 dB per W of pump power, coupled with bandwidths that are slightly smaller than the erbium amplifiers, Figure 19.18.

Brillouin scattering is a very efficient non-linear amplification mechanism that can realise high gains with modest optical pump powers (approximately 1 mW). However,

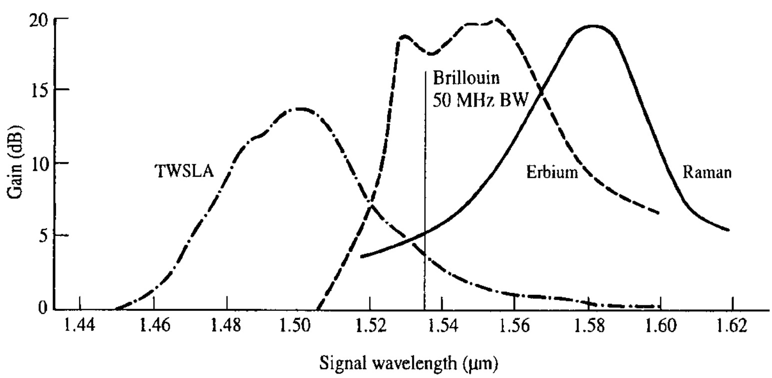


Figure 19.18 *Comparison of the gain of four distinct optical amplifier types (source: Cochrane, 1990, reproduced with the permission of British Telecommunications plc.).*

the bandwidth of only 50 MHz, Figure 19.18, is very limited in pure silica which makes such devices more applicable as narrowband tunable filters. This limited bandwidth fundamentally restricts the brillouin amplifier to relatively low bit rate communication systems.

A comprehensive comparison of the features of optical amplifiers is premature. However, what is clear is that long-haul optical transmission systems (10,000 km) are now feasible, with fibre amplifier based repeaters, and bit rates of 2 to 10 Gbit/s. At the present time TWSLA and erbium amplifiers generally require similar electrical pump power but TWSLAs achieve less gain, Figure 19.18, due to coupling losses. Erbium fibre amplifiers have the lowest noise and WDM channel crosstalk performance of all the amplifier types reported but high splice reflectivities can cause these amplifiers to enter the lasing condition. With the exception of brillouin, these amplifiers can be expected to be used across a broad range of system applications including transmitter power amplifiers, receiver preamplifiers, in-line repeater amplifiers and switches. The key advantage of EDFAs is that the lack of conversion to, and from, electrical signals for amplification gives rise to the 'dark fibre' – a highly reliable data super highway operating at tens of Gbit/s.

19.5.6 Optical repeater and link budgets

The electro-optic repeater is similar to the metallic line regenerator of Figures 6.15 and 6.30. For monomode fibre systems the light emitter is a laser diode and the detector uses an APD. The symbol timing recovery circuit uses zero crossing detection of the equalised received signal followed by pulse regeneration and filtering to generate the necessary sampling signals. Due to the high data rates, the filters often use surface acoustic wave devices [Matthews] exploiting their high frequency operation combined with acceptable Q value. The received SNR is given by:

$$\frac{S}{N} = \frac{I_p^2}{2q_e B(I_p + I_D) + I_n^2} \tag{19.1}$$

where I_p is the photodetector current, I_D is the leakage current, q_e is the charge on an electron, B is bandwidth and I_n is the RMS thermal noise current given by:

$$I_n^2 = \frac{4kTB}{R_L} \tag{19.2}$$

For received power levels of –30 dBm, $I_n^2 >> 2q_e B(I_p + I_D)$ giving, typically, a 15 to 20 dB SNR and hence an OOK BER in the range 10^{-7} to $< 10^{-10}$ [Alexander].

There are many current developments concerned with realising monolithic integrated electro-optic receivers. Integrated receivers can operate with sensitivities of –20 to –30 dBm and a BER of 10^{-10} at 155, 625 and 2488 Mbit/s, with a 20 dB optical overload capability. They are optimised for low crosstalk with other multiplex channels.

The power budget for a typical link in a fibre transmission system might have a transmitted power of 3 dBm, a 60 km path loss of 28 dB, a 1 dB path dispersion allowance and 4 dB system margin to give a –30 dBm received signal level which is consistent with a low cost 155 Mbit/s transmission rate. The higher rate of 2.5 Gbit/s, with a similar receiver sensitivity of –30 dBm, would necessitate superior optical interfaces on such a 60 km link.

Long haul experiments and trials have achieved bit rates from 140 Mbit/s to 10 Gbit/s using up to 12 cascaded amplifiers spanning approximately 1000 km. BERs of 10^{-4} to 10^{-8} have been measured on a 500 km, five amplifier system, operating at 565 Mbit/s in which the individual amplifier gains were 7 to 12 dB [Cochrane *et al.* 1993].

EXAMPLE 19.3

A monomode, 1.3 μm, optical fibre communications system has the following specification:

Optical output of transmitter, P_T	0.0 dBm
Connector loss at transmitter, L_T	2.0 dB
Fibre specific attenuation, γ	0.6 dB/km
Average fibre splice (joint) loss, L_S	0.2 dB
Fibre lengths, d	2.0 km
Connector loss at receiver, L_R	1.0 dB
Design margin (including dispersion allowance), M	5.0 dB
Required optical carrier power at receiver, C	–30 dBm

Find the maximum loss-limited link length which can be operated without repeaters.

Let estimated loss-limited link length be D' km and assume, initially, that the splice loss is distributed over the entire fibre length.

$$\begin{aligned}\text{Total loss} &= L_T + (D' \times \gamma) + \left(\frac{D'}{d} \times L_S\right) + L_R + M \\ &= 2.0 + 0.6D' + \left(\frac{0.2}{2.0} \times D'\right) + 1.0 + 5.0 \\ &= 8.0 + 0.7D' \text{ dB}\end{aligned}$$

$$\text{Allowed loss} = P_T - C = 0.0 - (-30) = 30.0 \text{ dB}$$

Therefore:

$$8.0 + 0.7D' = 30$$

$$D' = \frac{30.0 - 8.0}{0.7} = 31.4 \text{ km}$$

The assumption of distributed splice loss means that this loss has been over estimated by:

$$\begin{aligned}\Delta L_S &= L_s\,[\,D' - int\,(D'/d)d\,]\,/\,2 \\ &= 0.2\,[\,31.4 - int\,(31.4/2)2\,]\,/\,2 \\ &= 0.14 \text{ dB}\end{aligned}$$

This excess loss can be reallocated to fibre specific attenuation allowing the link length to be extended by:

$$\Delta D = \Delta L_S/\gamma = 0.14/0.6 = 0.2 \text{ km}$$

The maximum link length, D, therefore becomes:

$$D = D' + \Delta D = 31.4 + 0.2 = 31.6 \text{ km}$$

19.5.7 Optical FDM

With the theoretical 50 THz of available bandwidth in an optical fibre transmission system, and with the modest linewidth of modern optical sources, it is now possible to implement optical FDM and transmit multiple optical carriers along a single fibre. The optical carriers might typically be spaced by 1 nm wavelengths. With the aid of optical filters these signals can be separated in the receiver to realise wavelength division multiplex (WDM) communications [Oliphant *et al.*]. It is envisaged that eventually up to 100 separate channels could be accommodated using this technique but the insertion loss of the multiplexers and crosstalk between channels still needs to be assessed. It has been demonstrated that 10 such combined signals, each modulated at 10 Gbit/s, can be transmitted through a practical fibre, and amplified using a single fibre amplifier without having to demultiplex the signals. WDM promises to increase by a hundredfold the information carrying capacity of fibre based systems when the necessary components for modulators and demodulators are fully developed.

Soliton transmission uses pulses that retain their shape for path lengths of thousands of kilometres due to the reciprocal effects of chromatic dispersion and a refractive index which is a function of intensity. Such systems have been constructed for 1,000 km paths with bit rates of 10 to 50 Gbit/s. In the laboratory, 10^6 km recirculating links have been demonstrated, corresponding to many circulations of the earth before the received SNR is unacceptable [Cochrane *et al.* 1993].

19.6 Network advantages of SDH systems

In the current plesiochronous hierarchy, within the transport signal at 140 Mbit/s, we may want to route component signals, for example 2 Mbit/s streams or tributaries, through the network. This requires us to demultiplex the transport signals layer-by-layer through the hierarchy, switch the tributary signals, and then remultiplex them into the next transport signal, Figure 19.9.

In the SDH, individual component signals do not have to be demultiplexed to their original bit rate; instead they are incorporated into a signal called a 'container' which can be handled in a convenient way throughout the network, Figure 19.14. Direct access to these component signals is thus possible, Figure 19.19. The result is a considerable reduction in multiplexer hardware in SDH systems, combined with improved operational flexibility.

With the introduction of SDH the opportunity can now be taken to replace network layers and topologies with those better suited to long haul resilient networks. With the

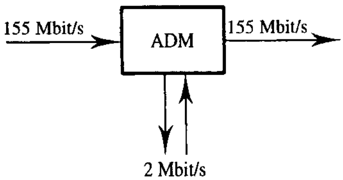


Figure 19.19 *Add-drop multiplexer (ADM) for simplified channel dropping which permits multiplexing into ring networks. (Compare with Figure 19.9.)*

availability of, very high speed, flexible SDH links it now becomes economic to reconsider the structure of the PSTN and replace simple (multiple) two-way transmission paths between the major centres, in which terminal multiplexers are two port or tributary-line systems, by high speed optical rings, as illustrated in Figure 19.20. The three port (input line, output line and tributary) add-drop multiplexers (ADMs), Figure 19.19, provide ring access and egress. This structure (Figure 19.20) will form the heart of the PDN and is fundamentally more reliable and less costly than the previous solution. Figure 19.20 represents an enhanced version of Figure 18.14. When the rings incorporate independent clockwise and anti-clockwise transmission circuits, as in the FDDI example described in Chapter 18, they offer immense flexibility and redundancy allowing information to be transmitted, via the ADM, in either direction around the ring to its intended destination.

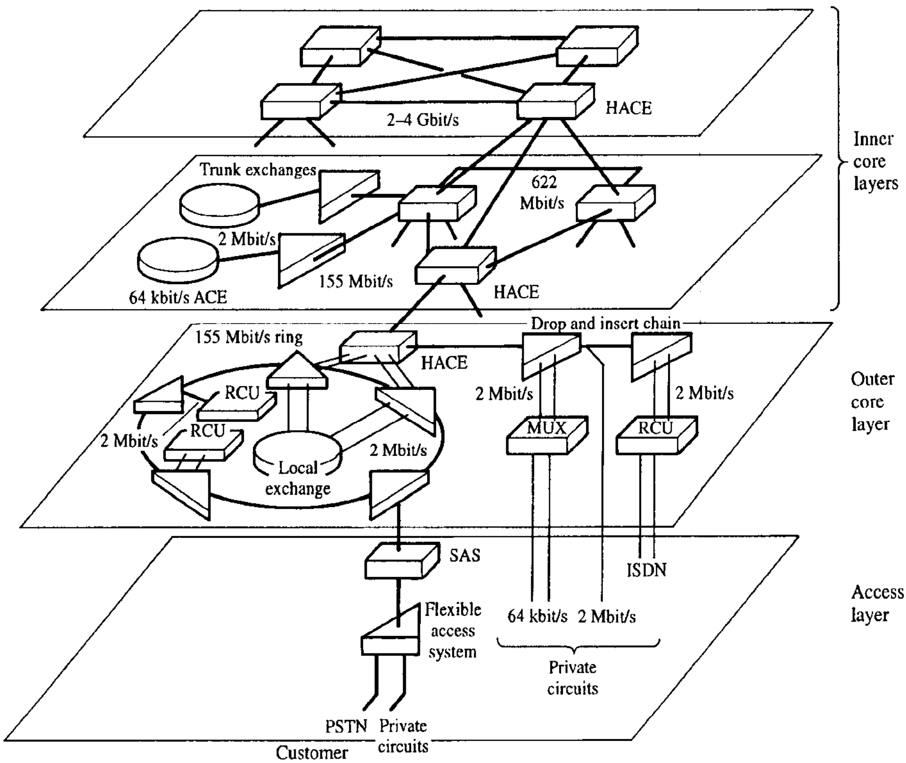
Outer-core topologies will be mainly rings of SDH multiplexers linking local exchanges, in contrast to a plesiochronous multiplex where all traffic is routed through a central site. The SDH ring structure with its clockwise and anti-clockwise routing is much more reliable than centre-site routing. Furthermore, the SDH ring based network has less interface, and other, equipment. Access regions will remain, principally, star topologies, but will probably be implemented using optical technology, Figure 19.21.

19.7 Data access

19.7.1 ISDN data access

ISDN digital access was opened in the UK in 1985 and provided basic rate access at 144 kbit/s and primary rate access at 2 Mbit/s to the multiplex hierarchical structure of Figure 19.1. The customer interface for primary rate access provides for up to 30 PCM communications channels (e.g. a PABX) under the control of a common signalling channel.

Basic rate access provides the customer with two independent communications channels at 64 kbit/s together with a common signalling channel at 16 kbit/s. International standards for ISDN access (I.420) have now been agreed within ITU. Communications or bearer channels (B-channels) operate at 64 kbit/s, whilst the signalling or data channel (D-channel) operates at 16 kbit/s giving the basic rate total of



HACE: Higher-order automatic cross-connect equipment
SAS: Service access switch
ACE: Automatic cross-connect equipment
RCU: Remote concentrator unit

Figure 19.20 *Probable future SDH transmission network hierarchy (source: Leakey, 1991, reproduced with the permission of British Telecommunications plc.).*

144 kbit/s. The basic rate voice/data terminal transmits, full duplex, over a two-wire link with a reach of up to 2 km using standard telephone local loop copper cables. The transceiver integrated circuits employ a 256 kbaud, modified DPSK, burst modulation technique, Chapter 11, to minimise RFI/EMI and crosstalk. The D channel is used for signalling to establish (initiate) and disestablish (terminate) calls via standard protocols. During a call there is no signalling information and hence the D channel is available for packet switched data transmission.

Data access at 64 kbit/s is used in low bit rate image coders for videophone applications, Chapter 16. For high quality two way confravision services with full TV (512 × 512 pixel) resolution reduced bit rate coders have been designed to use primary access at 2 Mbit/s. Access at 2 Mbit/s is also required to implement wide area networks, Chapter 18, or to carry cellular telephone traffic between cell sites, Chapter 15.

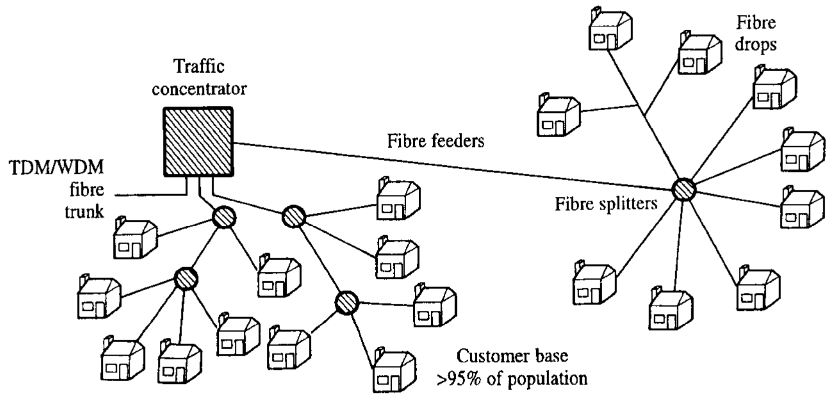


Figure 19.21 *Passive optical network for future local loop implementation.*

The layer 1 specification based on ITU-T I series recommendations [Fogarty] defines the physical characteristics of the user-network interface, Figure 19.22. The NT1 (network termination 1) terminates the transmission system and includes functions which are basically equivalent to layer 1 of the OSI architecture, Figure 18.12. The terminal equipment (TE) includes the ITU-T NT2 (network termination 2) function which

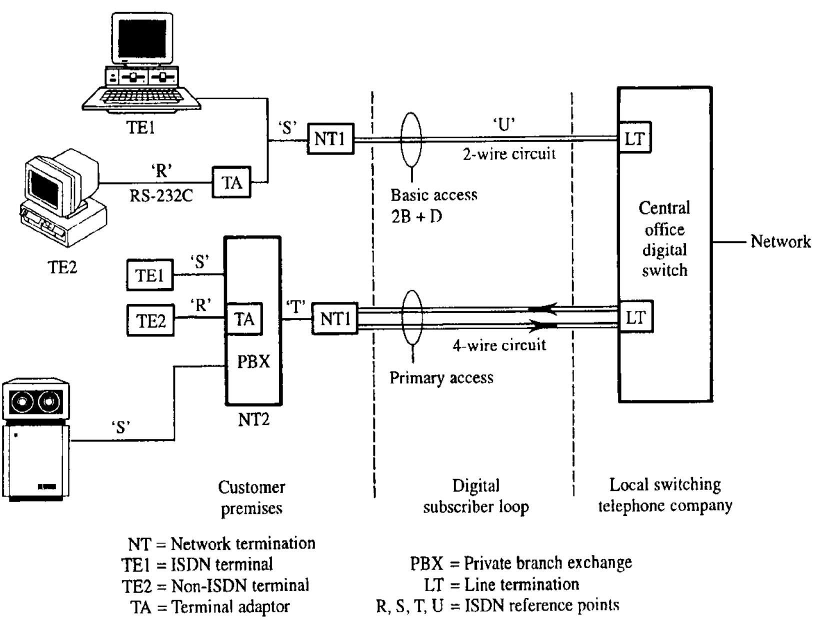


Figure 19.22 *Basic rate (144 kbit/s) and primary rate (2 Mbit/s) access to the ISDN.*

terminates ISO layers 1 to 3 of the interface. Figure 19.22 illustrates how digitised speech and data have access to the ISDN and includes the R, S, T and U ISDN reference points, which can be interconnected by standard interface integrated circuits.

Examples of TE1 equipments are ISDN telephone or fax machines which use the S interface. A TE2 might be a V.24 (RS232) data terminal or computer which requires the terminal adaptor (TA) to interface with the ISDN. The TA performs the processing to establish and disestablish calls over the ISDN and handles the higher level OSI protocol processing. For computer connection the TA is usually incorporated in the PC.

19.7.2 STM and ATM

Synchronous transfer mode (STM) and asynchronous transfer mode (ATM) both refer to techniques which deal with the allocation of usable bandwidth to user services. STM as used here is not to be confused with the synchronous transport module defined in section 19.4.3. In a digital voice network, STM allocates information blocks, at regular intervals (bytes/125 μs). Each STM channel is identified by the position of its time slots within the frame, Figure 19.5, which could easily be extended to a 30 channel, 2 Mbit/s system. STM works best when the network is handling a single service, such as the continuous bit-rate (bandwidth) requirements of voice, or a limited heterogeneous mix of services at fixed channel rates. Now, however, a dynamically changing mix of services requires a much broader range of bandwidths, and a switching capability adequate for both continuous traffic (such as voice and video conferencing) and non-continuous traffic (such as high-speed data and coded video traffic) in which bandwidth may change with time depending on the information rate.

While STM can provide data transfer services, the network operator must supply, and charge for, facilities with the full bandwidth needed by each service for 100% of the time – even if users require the peak bandwidth for only a small fraction of the time. The network therefore operates at low efficiency and the cost to users is prohibitive. This is not an attractive option for variable bit rate (VBR) traffic, such as coded video transmission, in which the data rate is dependent on how fast the image is changing.

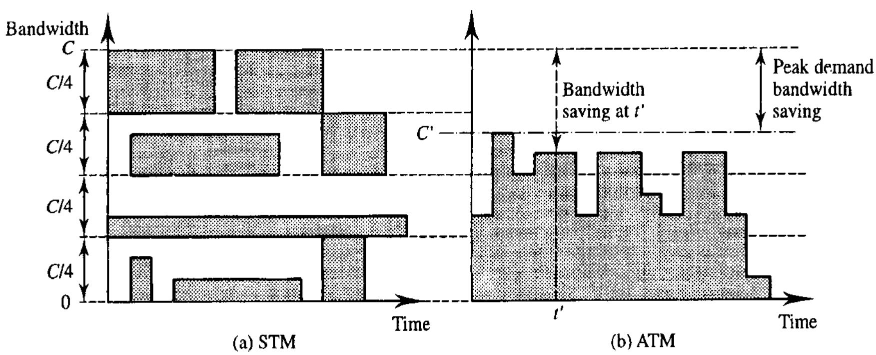


Figure 19.23 *Example of (a) STM and (b) ATM with mix of fixed and variable bit rate traffic.*

Figure 16.19 shows an example of such traffic for which the average data rate is very much smaller than the peak rate. When many VBR sources are averaged then the peak transmission rate requirement comes much closer to the average rate.

The structure of the ATM protocol improves on the limited flexibility of STM by sharing both bandwidth and time [de Prycker]. Instead of breaking down bandwidth into fixed, predetermined, channels to carry information, as shown schematically for STM in Figure 19.23(a), ATM transfers fixed-size blocks of information, called cells, whenever a service requires transmission bandwidth, in a manner analogous to a packet switched system, Chapter 17. Figure 19.23(b) illustrates the (statistical) multiplexing of the ATM traffic. When the transmission bandwidth is dynamically allocated to variable bit rate users, there is a consequent peak bandwidth saving ($C' < C$), provided that the packet overhead is small. ATM uses a 5 byte header combined with a 48 byte data packet representing a compromise between the optimum data packet lengths of 16 bytes, for audio, and 128 bytes for video traffic. (The 53 byte ATM cell also represents, more generally, a compromise between short cell lengths required for real time, low delay, traffic applications such as packet speech, and long cell lengths which are more efficient for data applications due to their reduced proportion of overhead bits.) CRC, section 10.8.1, is implemented on the header information only using the polynomial:

$$M(x) = x^8 + x^2 + x^1 + 1 \tag{19.3}$$

to achieve a single error correction, but multiple error detection, capability. In comparison to other packet data networks (e.g. packet speech) ATM achieves high speed (149.76 Mbit/s corresponding to the payload bit rate of the SDH STM-1) by using hardware VLSI chips, rather than software, for the protocol processing and switching at network nodes.

One of the first services to use an ATM network for efficient data transport between LANs and PCs was a high-speed switched data service which carried VBR traffic. The ATM layer allows much higher data transfer rates than is possible with X.25 packet-switched networks (Chapter 18). As a result of ATM's remarkable flexibility and efficiency, end users can enjoy very-high-bandwidth services. These services can be carried over long distances by the PSTN with, potentially, very attractive tariffs. When the power of ATM is joined with the bandwidth and transmission quality of ISDN, a much enhanced service is achieved.

The term asynchronous in ATM refers to the fact that cells allocated to the same connection may exhibit an irregular occurrence pattern, as cells are filled according to the actual demand. This is an unfortunate term as it implies that ATM is an asynchronous transmission technique which is not the case. ATM facilitates the introduction of new services in a gradual and flexible manner, and is now the preferred access technique to the ISDN, for packet speech, video and other variable bit rate traffic. Queuing theory, Chapter 17, allows the analysis of ATM cell throughput rates and losses. The routing switches described in Chapter 18 are used for the ATM interfaces. ATM can fit seamlessly into the SDH frames of Figures 19.12 and 19.13 by accommodating the cells directly into the SDH payload envelope.

19.7.3 The local loop

Half of the investment of a telephone company is in the connections between subscriber handsets and their local exchange. Furthermore, this part of the network generates the least revenue since local calls are often cheap or, as in the USA, free. The length of these connections is 2 km on average and they seldom exceed 7 km. In rural areas the expense of installing copper connections now favours radio access for the local loop implementation. ISDN access demands 144 kbit/s duplex operation over 4 to 5 km which requires sophisticated signal processing if copper pair cables are used.

Assuming that the local loop is to be used for speech telephony and low speed data connections only, its replacement by fibre systems will be very gradual. If, however, we were to combine this requirement with cable TV and many other broadband services such as videophone, Chapter 16, then there would be an immediate demand for wideband local loop connections.

There will thus be a progressive move from copper based conductors to a fibre based passive optical network (PON) for the local connection. This will not be based on the current structure of one dedicated wire pair, or fibre, per household because of the large fibre bandwidth, section 19.5. (Furthermore, with 750 million telephones worldwide it would take more than 300 years for manufacturers to produce all the required cable at current production rates!) The future local network is therefore likely to comprise wideband fibre feeders with splitters and subsequent single fibre drops to each household, Figure 19.21. (One problem with the PON configuration is that there is no longer a copper connection to carry the power required for standby telephone operation.)

19.8 Summary

Multiplexing of PCM–TDM telephone traffic has been traditionally provided using the plesiochronous digital hierarchy. The PDH frame rate is 8000 frame/s and its multiplexing levels, bit rates and constituent signals are as follows:

PDH-1	2.048 Mbit/s	30+2, byte interleaved, 64 kbit/s voice channels – the PCM primary multiplex group
PDH-2	8.448 Mbit/s	4 bit-interleaved PDH-1 signals
PDH-3	34.368 Mbit/s	4 bit-interleaved PDH-2 signals
PDH-4	139.264 Mbit/s	4 bit-interleaved PDH-3 signals

Bit rates increase by a little more than a factor of four at each successive PDH level to allow for small differences in multiplexer clock speeds. Empty slots in a multiplexer output are filled with justification bits as necessary. A serious disadvantage of PDH multiplexing is the multiplex mountain which must be scaled each time a lower level signal is added to, or dropped from, a higher order signal. This is necessary because bit interleaving combined with the presence of justification bits means that complete demultiplexing is required in order to identify the bytes belonging to a given set of voice channels.

The synchronous digital hierarchy (SDH) and its originating North American equivalent, SONET, will eventually replace the PDH. The principal advantage of SDH is that low level signals remain visible in the multiplexing frame structure. This allows lower level multiplexes (down to individual voice channels) to be added or dropped from higher order multiplex signals without demultiplexing the entire frame. This simplifies cross-connection of traffic from one signal multiplex to another. The SDH frame rate is 8000 frame/s and each frame contains one or more synchronous transport modules (STMs). The SONET frame rate is also 8000 frame/s and each contains one or more synchronous transport signals (STSs). The standard SONET/STM payload capacities, bit rates, and constituent signals are as follows:

SONET	STS-1	9×90 bytes	51.84 Mbit/s	
SDH	STM-1	9×270 bytes	155.52 Mbit/s	3 STS-1s
SDH	STM-4	9×1080 bytes	622.08 Mbit/s	4 STM-1s
SDH	STM-16	9×4320 bytes	2.488 Gbit/s	4 STM-4s

SONET signals with capacities based on other multiples of STS-1 are also possible. The capacity of an STM-1 is such that it can carry one PDH-4 signal which will facilitate the operation of PSTNs during the period in which both multiplexing schemes are in use.

SONET and SDH have been designed, primarily, to operate with optical fibre transmission systems. Optical sources may be coherent [Hooijmans] or incoherent. Laser diodes have narrow spectra and are therefore usually the choice for high performance, high bit rate links. LEDs are less spectrally pure, leading to greater dispersion and smaller useful bandwidth, but are cheaper. Optical detectors typically contain PIN diodes or avalanche photodiodes (APDs). APDs are more expensive but more sensitive. Typical optical transmit powers are 0 dBm and typical optical receiver powers are –30 dBm. An optical fibre repeater may be implemented using an optical detector, a conventional electronic repeater and an optical source. Optical amplifiers (e.g. TWSLAs) may also be used. The most recent types of optical amplifier are distributed and consist of doped fibre sections which are optically pumped and lase as the optical signal propagates through them.

Fibres currently operate, in decreasing order of attenuation, at wavelengths of 0.85, 1.3 and 1.5 μm. They can be divided into three types depending on the profile of their refractive index variations. Multimode step-index fibres have relatively large core dimensions and suffer from modal dispersion which limits their useful bandwidth. Multimode graded-index fibres also have large core dimensions but use their variation in refractive index to offset the difference in propagation velocity between modes resulting in larger available bandwidth. Monomode (step-index) fibres suffer only chromatic dispersion which arises partly from the frequency dependence of refractive index (material dispersion) and partly from the frequency dependence of a propagating electromagnetic mode velocity in a waveguide of fixed dimensions. These two contributions can be made to cancel at an operating wavelength around 1.5 μm, however, which also corresponds to a minimum in optical attenuation of about 0.15 dB/km. This wavelength is therefore an excellent choice for long, low dispersion, high bit rate, links. Repeaterless links, hundreds of kilometres long, operating at Gbit/s data rates are now possible. Wavelength division multiplexing (WDM) promises to increase the communications capacity of a single fibre still further.

SDH, combined with optical fibre transmission, has allowed a re-evaluation of the PDN network topology. Future access is likely to be via a passive optical network (PON) at ISDN basic (144 kbit/s) or primary (2 Mbit/s) rates. 155 Mbit/s rings will connect to a network of higher-order automatic cross-connect equipment (HACE) which will themselves be interconnected at bit rates of 155 and 622 Mbit/s and higher. The highest layer of cross-connect equipment will be fully interconnected with 2.4 Gbit/s links.

Asynchronous transfer mode (ATM) will provide efficient use of time and bandwidth resources in the access layers of the network when variable bit rate services are provided. ATM frames consist of 53 byte cells, 48 of which carry traffic and 5 of which carry overhead. At the higher network layers ATM cells will be carried within the payload envelopes of SDH frames.

19.9 Problems

19.1. How does a plesiochronous multiplex function?

19.2. Explain the notion of section, line and path as entities in an SDH transmission network. Taking an STS-1 frame as an example, where is the information concerning these entities carried in the SDH signal? What is the nature of the information?

19.3. What mechanism is used to allow an SDH SPE to pass between SDH networks which are not synchronised? How does this differ from the mechanism used to allow tributaries from the old plesiochronous system (e.g. 2.048 Mbit/s) to be taken in and out of an SDH system?

19.4. Explain the term add-drop in the context of multiplexers. Draw block diagrams to show why this function is simpler to perform in the SDH system than in the older PDH system.