WDM concepts and Components

. A powerful aspect of an optical communication link is that many different wavelengths can be sent along a signal fiber simultaneously (in the 1300 ~~to~~ 1600nm spectral band). The technology of combining a number of wavelengths onto the same fiber is known as wavelength division multiplexing or WDM.

→ Actually WDM is same as FDM used in microwave and satellite system, except that in WDM the wavelength must be properly ~~spe~~ spaced to avoid interference.

Key Features of WDM :-

1. capacity upgrade :-
2. Transparency
3. Wavelength Routing.
4. Wavelength switching

Operational Principles of WDM.

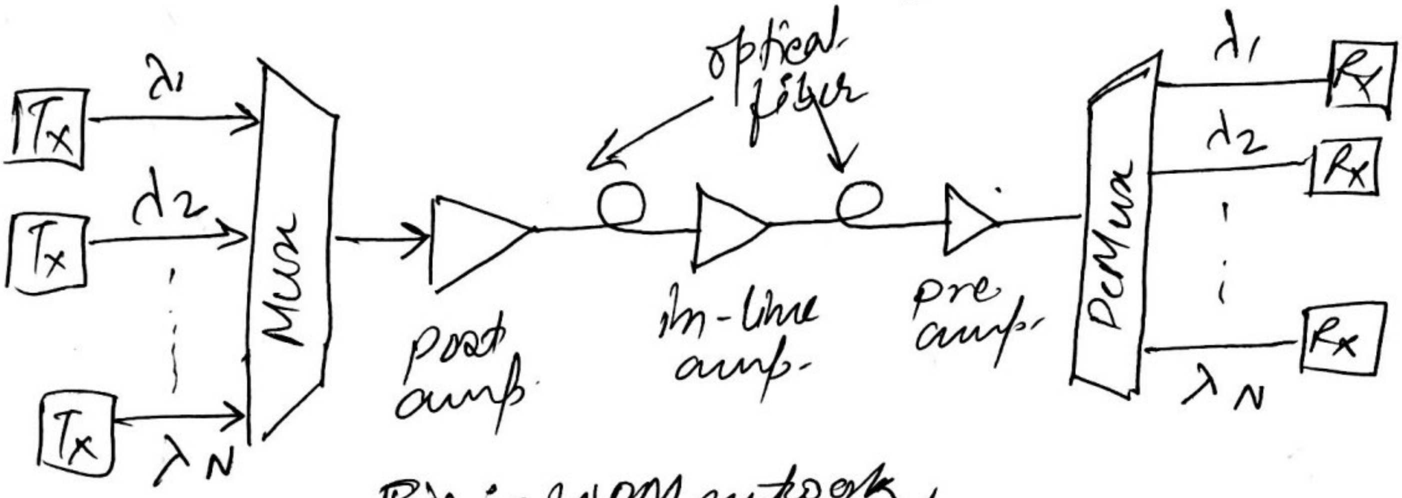


Fig :- WDM network.

→ The above figure shows a typical WDM link containing various types of optical amplifiers.

→ At the transmitting end ~~there~~ are several independently modulated light sources, each emitting signals at a unique wavelength

→ A multiplexer is needed to combine these optical output into a serial spectrum of closely spaced wavelength signals and couple them into a ~~serial spectrum of~~ single fiber.

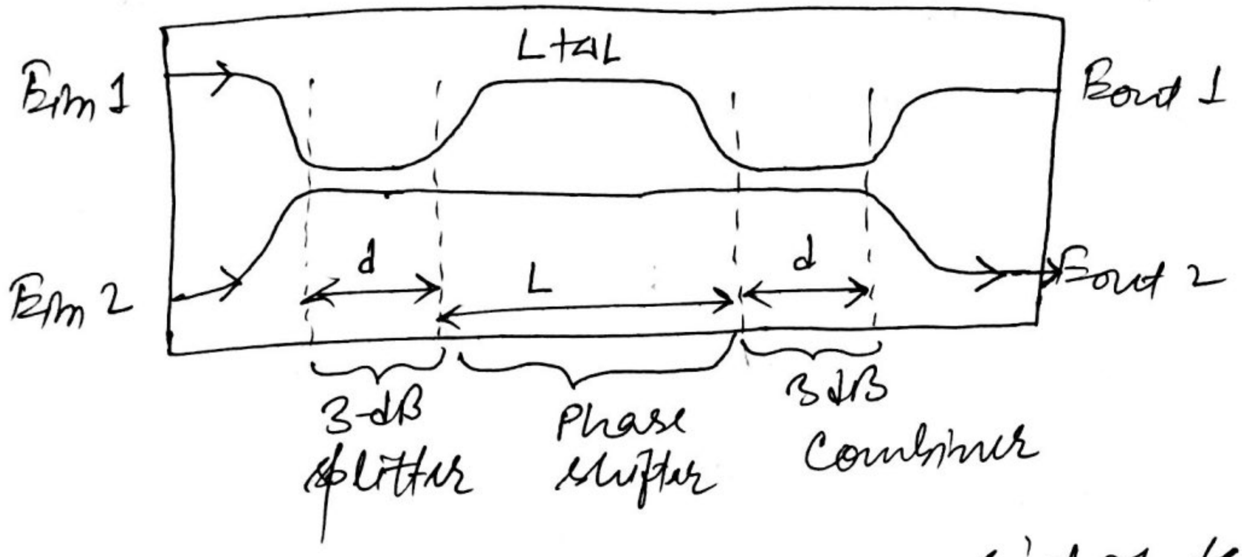
→ At the receiver end, a demultiplexer is required to ~~sef~~ separate the optical signals into appropriate detection channels for signal processing.

→ At the transmission end, the basic design challenges, is to have the multiplexer provide a low loss path from each optical source to the multiplexer o/p. Since the optical signals that are combined generally do not emit any significant amount of optical power outside of the channel spectral width.

→ A different requirement exists for the demultiplexer, since photoconductors are usually sensitive over a range of wavelengths, which could include all the WDM channels.

→ To prevent signals from entering a receiving channel. (or to give good channel isolation) the demultiplexer must exhibit narrow spectral operation or very stable optical-filters, with sharp wavelength cutoff.

Mach Zehnder Interferometer Multiplexer



This (2×2) multiplexer consist of three stages, an initial 3-dB directional coupler which splits the i/p signals, a central section where one of the waveguide is longer by ΔL to give a wavelength-dependent phase shift between the two arms, and another 3dB coupler which recombines the signals at the o/p.

→ The function of this arrangement is that, by splitting the i/p beam and introducing a phase shift in one of the paths the recombined signals will interfere constructively at one o/p and destructively at the other o/p.

→ Thus the signal will finally emerge from only one o/p port.

The propagation matrix ($M_{coupler}$) for a coupler length 'd' is-

$$M_{coupler} = \begin{bmatrix} \cos kd & j\sin kd \\ j\sin kd & \cos kd \end{bmatrix}$$

where k is coupling coefficient

as we are using 3dB coupler, which divides the power equally

$$\left(2kd = \frac{\pi}{2}\right)$$

$$M_{coupler} = \frac{1}{\sqrt{2}}\begin{bmatrix} 1 & j \\ j & 1 \end{bmatrix}$$

The phase difference is given by

$$\Delta\phi = \frac{2\pi n_1}{\lambda} L - \frac{2\pi n_2}{\lambda}(L+\Delta L)$$

NOTE: This phase difference can arise either from a different length (given by ΔL) or through a refractive index difference if $(n_1 \neq n_2)$.

→ Considering $n_1 = n_2 = n_{eff}$
(effective refractive index)

$$\Delta\phi = \frac{2\pi n_{eff}}{\lambda} L - \frac{2\pi n_{eff}}{\lambda}(L+\Delta L)$$

$$= \frac{2\pi n_{eff}}{\lambda}(\cancel{L} - \cancel{L} - \Delta L)$$

$$= -\frac{2\pi n_{eff}}{\lambda}\Delta L$$

$$\Delta\phi = K\Delta L \qquad K = \left(-\frac{2\pi n_{eff}}{\lambda}\right)$$

For a given phase difference $\Delta\phi$, the propagation matrix:

$$M_{\Delta\phi} = \begin{bmatrix} \exp(jk\Delta L/2) & 0 \\ 0 & \exp(-jk\Delta L/2) \end{bmatrix}$$

The optical o/p fields E_{out1} and E_{out2} are related to E_{in1} and E_{in2} as.

$$\begin{bmatrix} E_{out1} \\ E_{out.2} \end{bmatrix} = M \begin{bmatrix} E_{in1} \\ E_{in2} \end{bmatrix}$$

where

$$M = M_{coupler} \cdot M_{\Delta\phi}$$

$$= j \begin{bmatrix} \sin\left(\frac{k\Delta L}{2}\right) & \cos\left(\frac{k\Delta L}{2}\right) \\ \cos\left(\frac{k\Delta L}{2}\right) & -\sin\left(\frac{k\Delta L}{2}\right) \end{bmatrix}$$

As we want to build a multiplexer, we need to have the i/p at different wavelength, that is E_{in1} at λ_1 and E_{in2} at λ_2, then E_{out1} and E_{out2} are

$$E_{out1} = j\left[E_{in1}(\lambda_1)\sin(k_1 \Delta L/2) + E_{in2}(\lambda_2)\cos(k_2 \Delta L/2)\right]$$

$$E_{out2} = j\left[E_{in1}(\lambda_1)\cos(k_1 \Delta L/2) - E_{in2}(\lambda_2)\sin(k_2 \Delta L/2)\right]$$

where $\left[k_j = \frac{2\pi n_{eff}}{\lambda_j}\right]$

The o/p power are found from light intensity, which is the square of the field strength.

$$P_{out\,1} = \sin^2(K_1 \Delta L/2) P_{in1} +$$
$$\cos^2\left(\frac{K_2 \Delta L}{2}\right) P_{in2}$$

$$P_{out\,2} = \cos^2\left(\frac{K_1 \Delta L}{2}\right) P_{in1} +$$
$$\sin^2\left(\frac{K_2 \Delta L}{2}\right) P_{in2}$$

If we want all the power from both i/p to leave the same o/p port,

then $\left(\frac{K_1 \Delta L}{2} = \pi\right), \left(\frac{K_2 \Delta L}{2} = \frac{\pi}{2}\right)$

(or) $$(K_1 - K_2)\Delta L = 2\pi n_{eff}\left(\frac{1}{\lambda_1} - \frac{1}{\lambda_2}\right)\Delta L = \pi$$

then
$$\Delta L = \left[2 n_{eff}\left(\frac{1}{\lambda_1} - \frac{1}{\lambda_2}\right)\right]^{-1}$$
$$= \frac{c}{2 n_{eff}\,\Delta\nu}$$

$\Delta\nu$ = freq^n separation of the two wavelength.

Erbium - Doped Fiber Amplifiers (EDFA)

→ The active medium in an optical fiber amplifier consist of a normally (10–30)m length of optical fiber, that has been lightly doped, with a rare-earth elements, such as Erbium (Er), ytterbium (Yb), neodyimium (Nd) etc. The host fiber material can be either standard silica, a fluoride-based glass.

→ The operating regions of these devices depends on the host material and the doping elements.

→ The most popular material for long distance telecommunication applications is a silica fiber doped with Erbium (Er), which is known as an Erbium doped fiber amplifier (EDFA).

Amplification Mechanism

→ The semiconductor optical amplifiers use external current injection to excite electrons to higher energy levels, but in optical fiber amplifiers use optical pumping.

→ In this process one uses photons to directly raise electrons into excited states.

→ The optical pumping process requires the use of three energy levels.

→ The top energy level. to which the electron is elevated must lie above the desired lasing level.

→ After reaching its excited state, the electron must release some of its energy and drop to the desired lasing level.

→ From this level, a signal photon can then trigger it into stimulated emission, whereby it releases its remaining energy in the form of a new photon, with a wavelength identical to that of the signal photon.

→ For better understanding, how an EDFA works, we need to look at the energy level structure of the Erbium (Er).

→ The Er atom in silica are actual (Er^{3+}) ions, which are Erbium (Er) atoms have lost three of their ions to higher energy states.

→ *(diagram)

→ The two principal levels for telecommunication application are a Metastable level ($I_{13/2}$ level) and Pump level ($I_{11/2}$) level.

→ The term Metastable means that the lifetime for transition from this state to the ground state are very long compared with the lifetimes of the states that led to this level.

→ The metastable, the pump and the ground-state levels are actually bands of closely spaced energy levels that forms ~~a~~ due to the effect known as Stark Splitting.

→ The metastable band is ~~spot~~ separated from the bottom of the ground state level by an energy gap ranging from 0·814 eV to 0·841 eV.

→ The energy band for the pump level exists at a 1·27 eV separation from the ground state.

→ The gap between the top of the ground state level and the bottom of the metastable band is around 0·775 eV.

→ In normal-operation a pump laser emitting 980 nm. photons is used to excite ions from the ground state to the pump level. (1).

→ The excited ions decay very quickly from the pump level to the metastable band. (2).

→ During this decay, the excess energy is released as phonons or mechanical vibrations in the fiber.

→ Within the metastable band, the electrons of the excited ions tend to populate the lower end of the band.

→ Another possible pump wavelength is 1480 nm. The energy of these pump photons is very similar to the signal photon energy, but slightly higher.

→ The absorption of a 1480 nm pump photon excites an electron from the ground state directly to the lightly populated top of the metastable state. (3).

→ These electrons then tend to move down to the more populated lower end of the metastable level. (4).

→ Some of the ions sitting at the metastable level can decay back to the ground state in the absence of an externally stimulated photon, as shown by the transition (5).

→ This decay phenomanon is known as spontaneous emission.

→ Two more types of transitions occur when a photon of band gap energy b/w the ground state and the metastable state falls on the device.

→ first a small portion of the external photons will be absorbed by the ions in the ground state, which raise these ions to the metastable level. (6).

→ Second in the stimulated emission process (7) a signal photon triggers an excited ion to drop to the ground level, thereby emitting a new photon of the same energy.

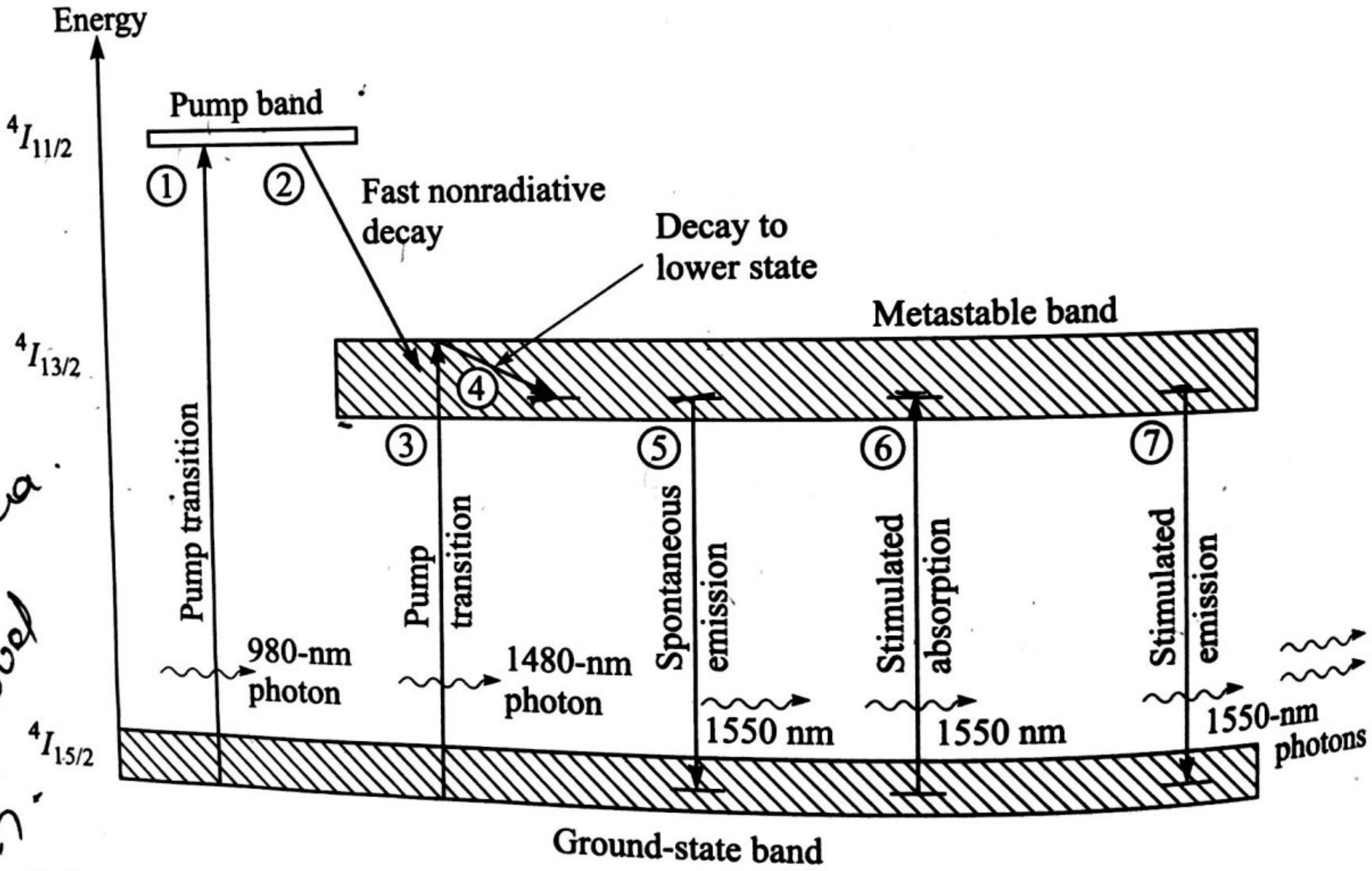


FIGURE 11-4

Simplified energy-level diagrams and various transition processes of Er^{3+} ions in silica.

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Q. Consider an EDFA being pumped at 980 nm with a 30mW pump power. If the gain at 1550nm is 20dB, then find out maximum i/p power.

$$(\text{gain})\,dB = 10 \log_{10}(\text{gain}).$$

$$\Rightarrow 20 = 10 \log_{10}(\text{gain})$$

$$\Rightarrow \text{gain} = 10^{2}$$

$$\Rightarrow \text{gain} = 100$$

$$P_{s(in)} = \frac{\left(980/1550\right)(30mW)}{100-1}$$

$$= 190\mu W$$

$$P_{s(out)} = P_{s(in)} + \frac{\lambda_p}{\lambda_s} P_{p(in)}$$

$$= 190\mu W + 0.63\,(30\mu W)$$

$$= 19.1mW$$

12.2 SONET/SDH

With the advent of fiber optic transmission lines, the next step in the evolution of the digital time-division-multiplexing (TDM) scheme was a standard signal format called *synchronous optical network (SONET)* in North America and *synchronous digital hierarchy (SDH)* in other parts of the world. This section addresses the basic concepts of SONET/SDH, its optical interfaces, and fundamental network implementations. The aim here is to discuss only the physical-layer aspects of SONET/SDH as they relate to optical transmission lines and optical networks. Topics such as the detailed data format structure, SONET/SDH operating specifications, and the relationships of switching methodologies such as asynchronous transfer mode (ATM) with SONET/SDH are beyond the scope of this text. These can be found in numerous sources, such as those listed in Refs. 13–15.

12.2.1 Transmission Formats and Speeds

In the mid-1980s, several service providers in the USA started efforts on developing a standard that would allow network engineers to interconnect fiber optic transmission equipment from various vendors through multiple-owner trunking networks. This soon grew into an international activity, which, after many differences of opinion of implementation philosophy were resolved, resulted in a series of ANSI T1.105 standards[16] for SONET and a series of ITU-T recommendations for SDH.[17] Of particular interest here are the ANSI T1.105.06 standard and the ITU-T G.957 recommendation. Although there are some implementation differences between SONET and SDH, all SONET specifications conform to the SDH recommendations.

Figure 12-5 shows the basic structure of a SONET frame. This is a two-dimensional structure consisting of 90 columns by 9 rows of bytes, where one byte

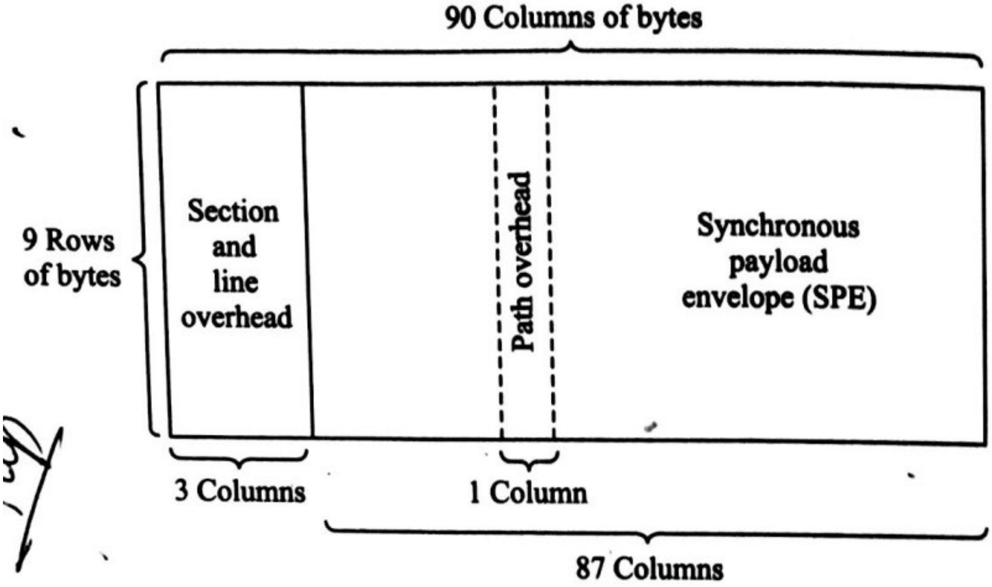


FIGURE 12-5
Basic structure of an STS-1 SONET frame.

is eight bits. Here, in standard SONET terminology, a *section* connects adjacent pieces of equipment, a *line* is a longer link that connects two SONET devices, and a *path* is a complete end-to-end connection. The fundamental SONET frame has a 125-μs duration. Thus, the transmission bit rate of the basic SONET signal is

$$\text{STS-1} = (90\ \text{bytes/row})(9\ \text{rows/frame})(8\ \text{bits/byte})/(125\ \mu\text{s/frame}) = 51.84\ \text{Mb/s}$$

This is called an STS-1 signal, where STS stands for *synchronous transport signal*. All other SONET signals are integer multiples of this rate, so that an STS-*N* signal has a bit rate equal to *N* times 51.84 Mb/s. When an STS-*N* signal is used to modulate an optical source, the *logical STS-N signal* is first scrambled to avoid long strings of ones and zeros and to allow easier clock recovery at the receiver. After undergoing electrical-to-optical conversion, the resultant *physical-layer optical signal* is called OC-*N*, where OC stands for *optical carrier*. In practice, it has become common to refer to SONET links as OC-*N* links. Algorithms have been developed for values of *N* ranging between 1 and 255. However, in the range from 1 to 192, the ANSI T1.105 standard recognizes only the values $N = 1, 3, 12, 24, 48$, and 192.

In SDH the basic rate is equivalent to STS-3, or 155.52 Mb/s. This is called the *synchronous transport module—level 1* (STM-1). Higher rates are designated by STM-*M*. (Note: Although the SDH standard uses the notation "STM-*N*," here we use the designation "STM-*M*" to avoid confusion when comparing SDH and SONET rates.) Values of *M* supported by the ITU-T recommendations are $M = 1, 4, 16$, and 64. These are equivalent to SONET OC-*N* signals, where $N = 3M$ (i.e., $N = 3, 12, 48$, and 192). This shows that, in practice, to maintain compatibility between SONET and SDH, *N* is a multiple of three. Analogous to SONET, SDH first scrambles the logical signal. In contrast to SONET, SDH does not distinguish between a logical electrical signal (e.g., STS-*N* in SONET) and a physical optical signal (e.g., OC-*N*), so that both signal types are designated by STM-*M*. Table 12-2 lists commonly used values of OC-*N* and STM-*M*.

Referring to Fig. 12-5, the first three columns comprise transport overhead bytes that carry network management information. The remaining field of 87 columns is called the *synchronous payload envelope* (SPE) and carries user data plus nine bytes of path overhead (POH). The POH supports performance monitoring by the end equipment, status, signal labeling, a tracing function, and a user channel. The nine path-overhead bytes are always in a column and can be located anywhere in the SPE. An important point to note is that the synchronous byte-interleaved multiplexing in SONET/SDH (unlike the asynchronous bit interleaving used in earlier TDM standards) facilitates add/drop multiplexing of information channels in optical networks (see Sec. 12.2.4).

For values of N greater than 1, the columns of the frame become N times wider, with the number of rows remaining at nine, as shown in Fig. 12-6. Thus, an STS-3 (or STM-1) frame is 270 columns wide with the first nine columns containing overhead information and the next 261 columns being payload data. The line and section overhead bytes differ somewhat between SONET and SDH, so that a translation mechanism is needed to interconnect them. To obtain further details on the contents of the frame structure and the population schemes for the payload field, the reader is referred to the SONET and SDH specifications.[16,17]

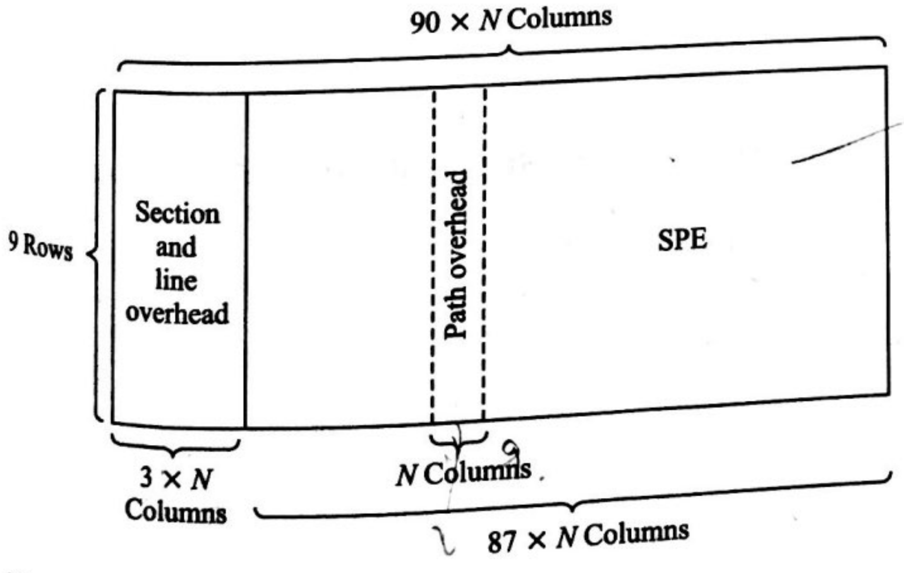


FIGURE 12-6
Basic format of an STS-*N* SONET frame.

12.2.3 SONET/SDH Rings

→ Imp IAT-3 VTU

A key characteristic of SONET and SDH is that they are usually configured as a ring architecture. This is done to create *loop diversity* for uninterrupted service protection purposes in case of link or equipment failures. The SONET/SDH rings are commonly called *self-healing rings*, since the traffic flowing along a certain path can automatically be switched to an alternate or standby path following failure or degradation of the link segment.

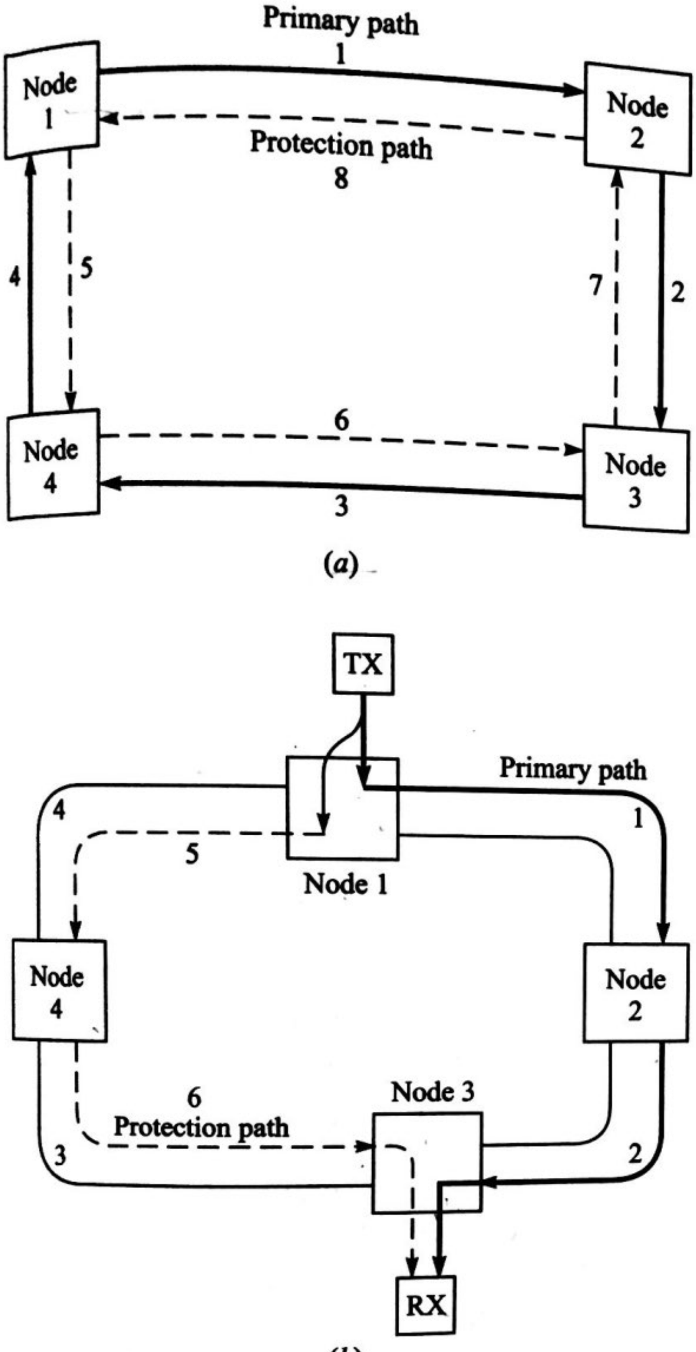
Three main features, each with two alternatives, classify all SONET/SDH rings, thus yielding eight possible combinations of ring types. First, there can be either two or four fibers running between the nodes on a ring. Second, the operating signals can travel either clockwise only (which is termed a *unidirectional ring*) or in both directions around the ring (which is called a *bidirectional ring*). Third, protection switching can be performed either via a line-switching or a path-switching scheme.[18–21] Upon link failure or degradation, *line switching* moves all signal channels of an entire OC-N channel to a protection fiber. Conversely, *path switching* can move individual payload channels within an OC-N channel (e.g., an STS-1 subchannel in an OC-12 channel) to another path.

Of the eight possible combinations of ring types, the following two architectures have become popular for SONET and SDH networks:

- two-fiber, unidirectional, path-switched ring (two-fiber UPSR).
- two-fiber or four-fiber, bidirectional, line-switched ring (two-fiber or four-fiber BLSR).

The common abbreviations of these configurations are given in parentheses. They are also referred to as unidirectional or bidirectional self-healing rings (USHRs or BSHRs), respectively.

Figure 12-7 shows a two-fiber unidirectional path-switched ring network. By convention, in a unidirectional ring the normal working traffic travels clockwise around the ring, on the *primary path*. For example, the connection from node 1 to



(a)

(b)

BW cap

FIGURE 12-7
(*a*) Generic two-fiber unidirectional network with a counter-rotating protection path. (*b*) Flow of primary and protection traffic from node 1 to node 3.

node 3 uses links 1 and 2, whereas the traffic from node 3 to node 1 traverses links 3 and 4. Thus, two communicating nodes use a specific bandwidth capacity around the entire perimeter of the ring. If nodes 1 and 3 exchange information at an OC-3 rate in an OC-12 ring, then they use one-quarter of the capacity around the ring on all the primary links. In a unidirectional ring the counterclockwise path is used as an alternate route for protection against link or node failures. This *protection path* (links 5–8) is indicated by dashed lines. To achieve protection, the signal from a transmitting node is dual-fed into both the primary and protection fibers. This establishes a designated protection path on which traffic flows counterclockwise; namely, from node 1 to node 3 via links 5 and 6, as shown in Fig. 12-7.

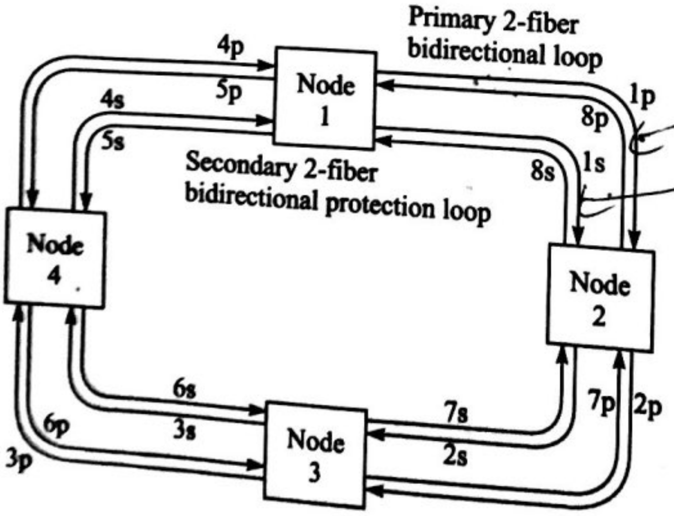
Consequently, two identical signals from a particular node arrive at their destination from opposite directions, usually with different delays, as denoted in Fig. 12-7*b*. The receiver normally selects the signal from the primary path. However, it continuously compares the fidelity of each signal and chooses the alternate signal in case of severe degradation or loss of the primary signal. Thus, each path is individually switched based on the quality of the received signal. For example, if path 2 breaks or equipment in node 2 fails, then node 3 will switch to the protection channel to receive signals from node 1.

Figure 12-8 illustrates the architecture of a four-fiber bidirectional line-switched ring. Here, two primary fiber loops (with fiber segments labeled 1p through 8p) are used for normal bidirectional communication, and the other two secondary fiber loops are standby links for protection purposes (with fiber segments labeled 1s through 8s). In contrast to the two-fiber UPSR, the four-fiber BLSR has a capacity advantage since it uses twice as much fiber cabling and because traffic between two nodes is sent only partially around the ring. To see this, consider the connection between nodes 1 and 3. The traffic from node 1 to node 3 flows in a clockwise direction along links 1p and 2p. Now, however, in the return path the traffic flows counterclockwise from node 3 to node 1 along links 7p and 8p. Thus, the information exchange between nodes 1 and 3 does not tie up any of the primary channel bandwidth in the other half of the ring.

BLSR

To see the function and versatility of the standby links in the four-fiber BLSR, consider first the case where a transmitter or receiver circuit card used on the primary ring fails in either node 3 or 4. In this situation, the affected nodes detect a loss-of-signal condition and switch both primary fibers connecting them to the secondary protection pair, as shown in Figure 12-9. The protection segment between nodes 3 and 4 now becomes part of the primary bidirectional loop. The exact same reconfiguration scenario will occur when the primary fiber connecting nodes 3 and 4 breaks. Note that in either case the other links remain unaffected.

Now suppose an entire node fails, or both the primary and the protection fibers in a given span are severed, which could happen if they are in the same cable



#1
for normal bidire. comm.

are standby links for prote

FIGURE 12-8
Architecture of a four-fiber bidirectional line-switched ring (BLSR).

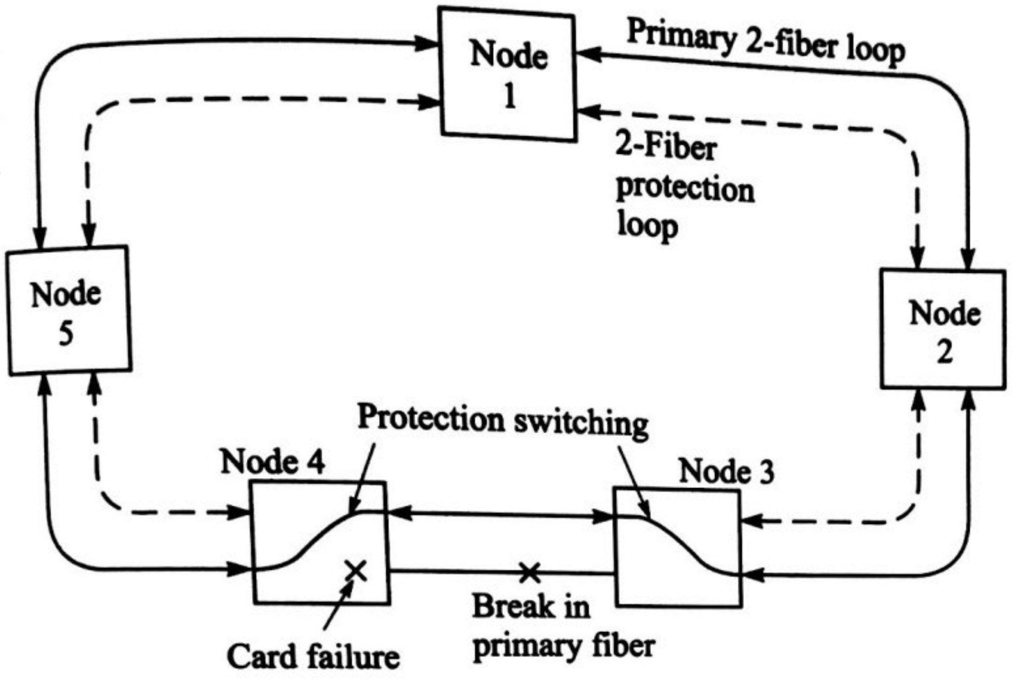


FIGURE 12-9
Reconfiguration of a four-fiber BLSR under transceiver or line failure.

duct between two nodes. In this case, the nodes on either side of the failed internodal span internally switch the primary-path connections from their receivers and transmitters to the protection fibers, in order to loop traffic back to the previous node. This process again forms a closed ring, but now with all of the primary and protection fibers in use around the entire ring, as shown in Fig. 12-10.

15.4 Wavelength routing networks

The optical layer is based on wavelength-dependent concepts when it lies directly above the physical layer. Hence the entire physical interconnected network provides wavelength signal service among the nodes using either single or multihop. This situation is illustrated in Figure 15.18. Three network nodes are interconnected using two wavelength channels

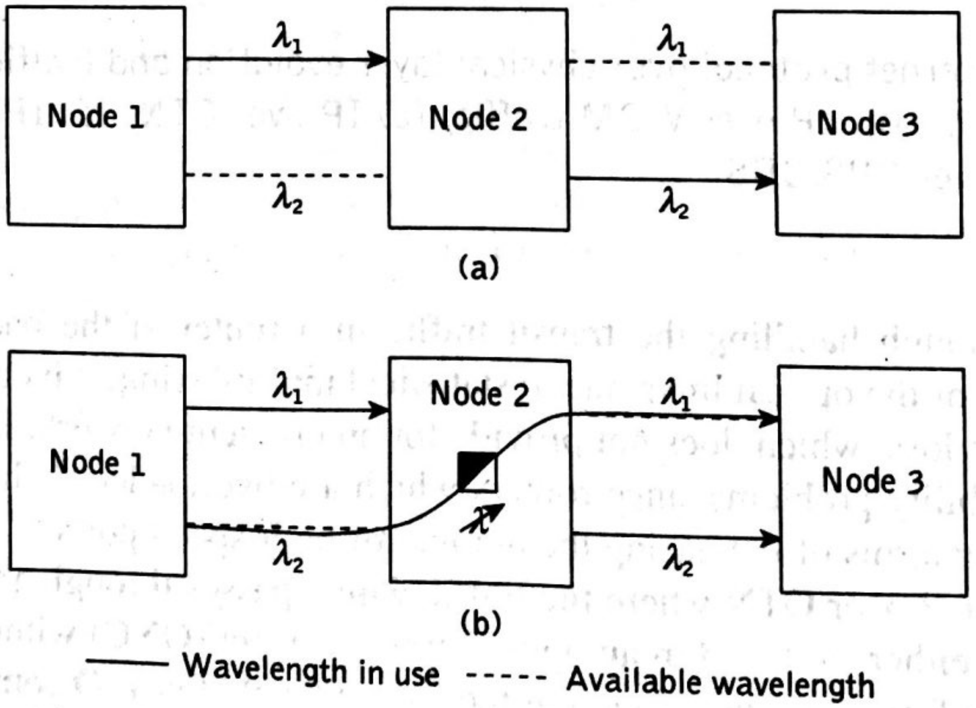


Figure 15.18 Wavelength-dependent interconnection: (a) fixed wavelength nodes; (b) wavelength convertible node (Node 2)

(i.e. λ_1 and λ_2) where the solid line connecting the nodes represents the available wavelength channel and the dashed line identifies that the wavelength channel is in use. If the network node 1 is required to connect with node 3 then as indicated in Figure 15.18(a) there is no single wavelength channel available to establish a lightpath between them. When a lightpath cannot be established on a link using a single wavelength channel it is referred to as a wavelength continuity constraint. A methodology to reduce this wavelength continuity constraint is to switch the wavelength channel at node 2 by converting the incoming wavelength λ_2 to λ_1 (which is available between nodes 2 and 3) to enable a link between node 2 and 3 to be established. This process is shown in Figure 15.18(b). Wavelength conversion (see Section 10.5) is required to convert from λ_2 to a compliant wavelength (i.e. λ_1) at the output port of network node 2 (which functions as an intermediate node) in order to provide a path. Hence the newly set up path uses two wavelength stages (i.e. two hops) to interconnect nodes 1 and 3. Such networks which employ wavelength conversion devices (or switches) are known as wavelength convertible networks.

Several network architectures can be employed to implement wavelength convertible networks. Three different WDM network architectures employing the wavelength conversion function are shown in Figure 15.19. Full wavelength conversion, where each network link utilizes a dedicated wavelength converter, is depicted in Figure 15.19(a). All the wavelength channels at the output port of the optical switch will be converted into their compliant wavelength channel by the appropriate wavelength converter (WC). For example, the topmost wavelength converter changes incoming λ_1 into λ_2 which is then connected to a multiplexer. There is no need, however, for wavelength conversion of the local add/drop channels.

It is not always required to provide the wavelength conversion function within every network node and it is more cost effective to implement networks with fewer and hence shared wavelength converters. So-called sparse wavelength convertible network architectures employing a number of wavelength converters as a wavelength converter bank (WCB) functioning on a shared basis per link and per node are shown in Figure 15.19(b) and (c), respectively. The arrangement of wavelength converters organized in a WCB is illustrated in the inset to Figure 15.19(b). This figure depicts a WCB servicing the optical fiber links where only the required wavelength channels are switched through the WCB (i.e. in Figure 15.19(b) the wavelength channel λ_2 is converted to wavelength channel λ_3). By contrast two optical switches are required to construct the shared per node wavelength convertible network architecture indicated in Figure 15.19(c). Optical switch 2 switches the converted wavelength channels to their designated nodes (i.e. in this case the wavelength channel λ_2 is converted to wavelength channel λ_3 via the shared WCB and is then switched through optical switch 2 to provide connection to the multiplexer).

A large number of wavelength channels on the network links, however, increase the complexity of switching nodes in ordinary OXCs which switch traffic only at the wavelength level. Moreover, the complexity worsens when multigranular OXCs (MG-OXCs) are used where the traffic is required to be accessed at multiple levels (i.e. at granularities such as the fiber, wavelength, digital cross-connects, etc.). In these cases the MG-OXC output traffic does not simply either terminate at or transparently pass through a node, but may also be required to transport from one layer to another via multiplexers/demultiplexers [Ref. 51]. This complexity can be reduced if more wavelength channels are grouped into one single waveband to be switched as a unique channel. Such waveband switching (WBS)

15.5 Optical switching networks

An optical switch represents the single most dynamic element in an optical network which traditionally can switch data between different ports of a network. Broadly, as with electronic switching, optical switching can be classified into two categories which are circuit and packet switching. An optical switch performs various digital logic operations (see Section 11.4.1) allowing signals to switch from one state to another. Therefore larger arrays of optical switches can switch signals from one port to another. These arrays of switches form circuit switching fabrics known as optical cross-connects (OXCs) which incorporate switching connections or lightpaths. A router, on the other hand, routes data packets instead of providing circuit-switched connectivity. In this case the data is split into packets which are routed separately through the network and then are reassembled at the receiving terminal to reconstitute the original message. This process provides for more efficient use of the available bandwidth.

Both circuit and packet switching techniques are used in high-capacity networks. In circuit-switched networks the connection must be set up between the transmitter and receiver before initiating the transfer of data. When the network resources remain dedicated to the circuit connection during the entire transfer and the complete message follows the same path, the circuit is said to be static. SDH/SONET (see Section 15.3.1) is an example of a static circuit-switched network. However, if the network resources can be reallocated without being physically disturbed the circuit is referred to as being dynamic.

15.5.1 Optical circuit-switched networks

In circuit-switched networks a connection is established using available network resources for the full duration of the transmission of a message. Once the complete message is successfully transmitted then the connection is removed. A circuit-switched environment requires that an end-to-end circuit be set up before the actual transmission can take place. A fixed share of network resources is then reserved for the specific transmission which no

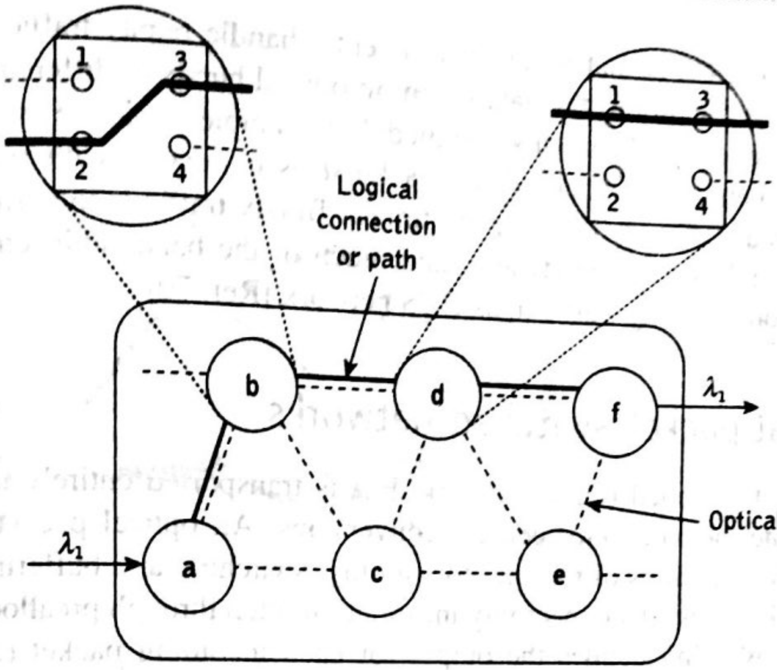


Figure 15.23 Optical circuit-switched network

other transmission can use. A request signal must, however, travel from the source to the destination and it should also be acknowledged before the transmission begins.

Figure 15.23 provides a block diagram illustrating an optical circuit-switched (OCS) network. In this configuration six optical nodes (i.e. a to f) are interconnected and a requested logical connection or path for optical signal wavelength, λ_1, is established producing a circuit path through network nodes a, b, d and f. Optical nodes of an OCS network contain optical switches where large multiport optical switches (i.e. a switching fabric) or an OXC (see Section 15.2.2) are used to establish connections between the desired input and output ports. Although different component enabling technologies (see Section 11.6) can be used to construct such optical switches, the basic optical switching function remains the same. Figure 15.23 illustrates this functionality at optical nodes b and d. For example, a 2 × 2 optical switch at node b enables cross-connection using ports 2 and 3, whereas node d employs a direct connection for ports 1 and 3. Hence a logical path or an optical circuit from node a to f is created for the lightpath using signal wavelength λ_1.

It should be noted that an optical switch can handle traffic from both SDH/SONET and IP networks (see Sections 15.3.1 and 15.3.5) with the limitation, however, that only in-service signals can use the available network resources. Furthermore, the wavelength continuity constraint (see Section 15.4) also limits the flexibility of OCS networks as lightpaths using the same wavelength can only carry the traffic from the source to the destination. Nevertheless this constraint can be overcome if the wavelength conversion function (see Section 10.5) is used at the output ports of the optical nodes to change the wavelength of the signal as required. In general OCS networks are suitable for implementation in public telecommunications networks (see Section 15.2.4) where a large volume of traffic is required to be switched in real time. OCS therefore has become an umbrella term to cover many network architectures based on two-way reservation [Ref. 67]. Various networks using the OCS concept have emerged to bring optical network services directly from the long-haul to business and residential customers [Refs 67–69].

A disadvantage of OCS is that it cannot efficiently handle bursty traffic (see Section 15.5.4). In such traffic conditions the data is sent in optical bursts of different lengths and therefore the resources cannot be readily assigned. For example, an active user (i.e. at peak times) needs large bandwidth when sending a burst as compared with relatively little bandwidth for a nonactive user (i.e. off-peak times). Bursty traffic is therefore characterized by both peak and average bandwidth, and much of the bandwidth remains unused with the transmission of bursty traffic in as OCS network [Ref. 70].

15.5.2 Optical packet-switched networks

In an optical packet-switched (OPS) network data is transported entirely in the optical domain without intermediate optoelectrical conversions. An optical packet switch performs the four basic functions of routing, forwarding, switching and buffering. The routing function provides network connectivity information often through preallocated routing tables, whereas forwarding defines the output for each incoming packet (i.e. based on a routing table). The switch directs each packet to the correct output (i.e. defined by the forwarding process) while buffering provides data storage for packets to resolve any contention problems which may occur during packet transmission.

Figure 15.24 shows the overall structure of a typical packet. It contains a header or label and the payload (i.e. data) and it requires a guard band to ensure the data is not overwritten. The label points to an entry in a lookup table that specifies to where the packet should be forwarded. Such a labeling technique is much faster than the traditional routing method where each packet is examined before a forwarding decision is made. At the receiving node these labels are required to be recognized from the lookup table and then the data is reassembled sequentially. Since labels define the routing criteria it is therefore sometimes referred to as label switching, which includes several functions involved in the labeling technique such as assignment (or writing) recognition (or reading), swapping (or exchanging) and forwarding etc. [Refs 71, 72].

The process of address lookup, however, can be replaced by address matching using optical correlators [Ref. 71], which are switching devices employing digital logic gates to perform optical pattern recognition similar to detecting an address from a lookup table. A set of optical correlators can therefore determine whether a packet is destined for a particular switch by correlating the address encoded into the packet with the switch's own address. If there is a match, the payload is extracted and processed. Otherwise, the packet is forwarded to the next switch.

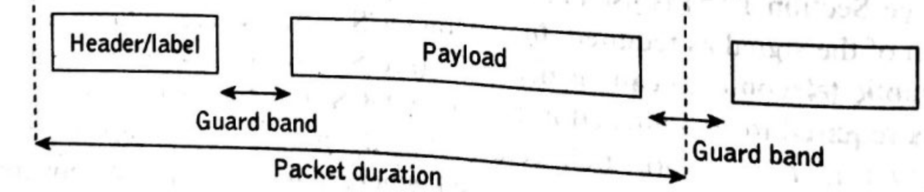


Figure 15.24 Optical packet-switched network packet format

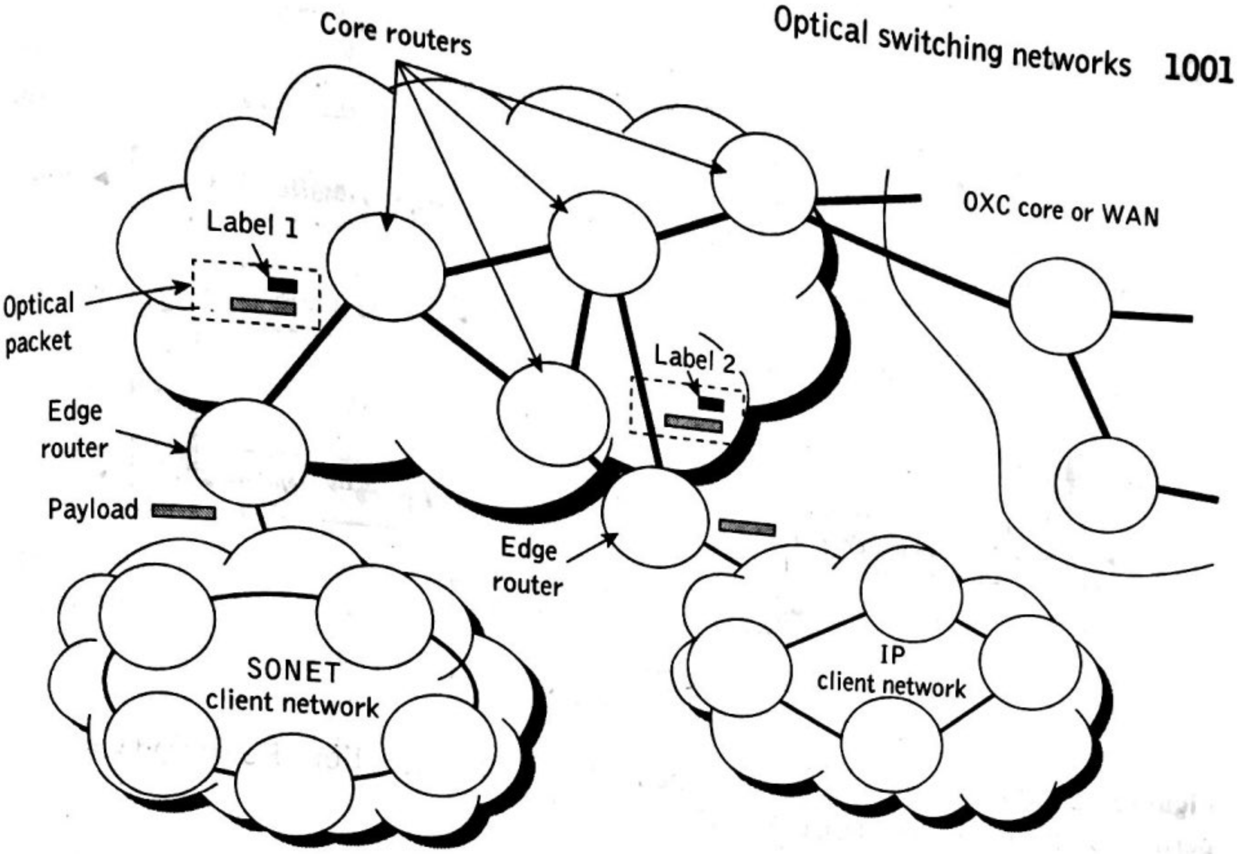


Figure 15.25 An optical packet-switched network. Reprinted with permission from Ref. 5 © IEEE 2006

The packets in an OPS network can carry different types of traffic (i.e. voice, data and video) and therefore such an optical packet switching scheme can integrate existing SDH/SONET and IP-based optical networks. An example of an OPS network is illustrated in Figure 15.25. It shows a long-haul or core network connected to both a SONET and an IP network. The edge routers (i.e. network nodes at the edges) perform the functions of attaching and detaching a label as identified for labels 1 and 2 attached to two different optical packets being transmitted to specific networks (i.e. to the IP and SONET client networks). Within the OPS network, however, the core router only processes the label where the content of the payload remains the same (i.e. the payload can carry ATM traffic or IP packets at different bit rates). This routing function typically involves the following four steps which are: (a) extraction of the label from the packet; (b) processing of the label to obtain routing information; (c) routing of the payload and contention resolution if necessary; and (d) rewriting of the label and recombining it with the payload. When an OPS network is implemented and only the label is processed electronically for routing purposes with the payload remaining in the optical domain, the OPS network is generally referred to as an optical label-switched (OLS) network.

Figure 15.26 depicts a generic OLS network configuration to route packets while also extracting and rewriting labels at input and output interfaces. In this particular implementation only the detached label is processed electronically and the payload (i.e. data) remains in optical buffers before being sent through the optical switch fabric to the desired output buffers. Finally, the routing processor and control section regenerate the label which is reattached with the data at the output interface.