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Introduction to Optical Networks

1.1 Introduction

Any technological development is always driven by the need and demand of the changes in society. The rapid evolution of communication networks from the basic telephone network to the present high-speed large area networks has come with the social need of people to communicate among themselves, with the increasing user demands for new applications, as well as advances in enabling technologies. The fast changes in the present-day telecommunication networks are also driven by the user's need to remain connected anytime and all the time, anywhere and everywhere in the world. The new applications, i.e. multimedia services, video-conferencing, interactive gaming, Internet services, and the World Wide Web, all demand very large bandwidths. Besides this, the user wants the unifying network underneath to be reliable, give the best services, and be cost-effective as well.

What we need today, therefore, is a communication network with high capacity and low cost, that is fast, reliable, and able to provide a wide variety of services from dedicated to best-effort services. The available transmission media best suited to meet most of these requirements is *optical fiber*. Besides having enormous bandwidth in terahertz ($\sim 10^{12}$ Hz), optical fiber has low loss and cost. It is lightweight, with strength and flexibility, and is immune to electromagnetic interference and noise. It is secure and has many more characteristics to make it an ideal high-speed transmission line, therefore optical fiber is most suitable to meet the traffic requirements in today's communication network. The enormous quantity of optical fiber laid throughout the world by the end of twentieth century is the foundation of the information super highway of optical network with huge bandwidth today.

1.1.1 Trends in Optical Networking

In order to increase the capacity of point-to-point links, optical fibers first replaced the coaxial and two-wire transmission lines in the existing communication networks. The capacity of the optical links in the network was further increased by using wavelength division multiplexing (WDM) in the laid fiber, thus having several wavelength channels carrying multiple data streams in a single fiber. But all the switching and routing operation in the network still remained in the electronic domain. In the real sense we do not define this network as an *all-optical network*. An all-optical network is the high-capacity telecommunication network which uses optical technology and components not only to provide large capacity optical fiber links for information transmission but also to do all the networking operations, such as *switching and routing* (i.e. facilitation of the correct and suitable path) of the signals on the required path, *grooming* of the low bit rate traffic signals to higher bit rate for better utilization of the enormous capacity of the fiber, and control and restoration functions in the network at the optical level in case of any failure in the network. The operation of the network at the optical or wavelength granularity level has many advantages. As an example, when a single wavelength carries a large number of independent connections and a failure occurs in a fiber cable, it is operationally much simpler to restore services by routing and processing an individual wavelength than to reroute each connection individually. Besides, optical switching functions consume much less power and have lower heat dissipation and footprint compared with their electronic counterparts. With the present optical technology, it is still not possible to achieve all these functions cost-effectively with ease. Hence, both optical and electronic devices are used, which makes the optical network not purely optical. These networks are indeed *hybrid* in nature at present, using both optical and electronic technology.

The communication network, which once supported telephone voice traffic only, now carries more data traffic supporting high-speed multimedia services. At the physical infrastructure level, the available optical components in the optical network can now support traffic at multiple speeds ranging up to tera-bits/sec (Tbps), with each fiber carrying a large number of wavelengths in the WDM systems. Also, along with the optical component infrastructure, the networks are becoming more flexible and agile due to the adoption of intelligent algorithms and protocols for networking, and therefore the network can now respond to new applications and demands with ease. The trend in optical networks is now toward SDON (software defined optical networking) to facilitate programmability of network operations to further increase agility and to provide users with more control over networking functions, thereby resulting in flexibility in the deployment of new services and protocols, better network utilization, QoS (quality of service), higher revenue generation from the

flexibility added in the network, and the user managing the network according to his/her requirements. There is a paradigm shift in optical networking now with SDON, which is a fast-evolving technology [1–4].

In the rest of the chapter we will give a brief overview of the optical networks and an introduction to the technologies, terminologies, and parameters involved. In order to have some understanding of the functionalities of different types of networks used, somewhat detailed stratification of a generic network is discussed, hoping for an easier understanding of the networks in subsequent chapters where these will be discussed in detail.

1.1.2 Classification of Optical Networks

On the basis of geographical reach, the telecom network can be subdivided in three categories: the access and local area network (LAN), the regional metropolitan area networks (MANs), and the backbone wide area network (WAN). This is shown in Figure 1.1.

Any two distant users in the access network communicate with each other through the switch/router (or exchange) to the rest of the network infrastructure. The access network can have a span of up to 20 km or so. The *access network* needs to be cost-effective as the cost has to be shared among a smaller number of individual users who are connected through it to the shared communication network underneath. The present-day high-speed optical solution to the access part is with passive optical networks (PONs), with many variants of the Ethernet passive optical network (EPON), gigabit passive optical network (GPON), and WDM PON, etc. The other lower speed access networks are provided by wireless (WiMax, Wi-Fi), cable modems, digital subscriber lines (DSLs), higher speed lines (T1/E1), etc. We discuss the access networks in detail in Chapter 4.

The *metro network* covers distances of a few kilometers to hundreds of kilometers. The metro network aggregates the traffic from the access networks. The technologies used in metro networks are a lot different from those in access networks. Metro networks generally have a ring physical architecture using the legacy Synchronous Optical NETWORKing (SONET)/synchronous digital hierarchy (SDH), asynchronous transfer mode (ATM), or optical transport network (OTN) networks. A node (router) of the ring or mesh collects or distributes the traffic of the access network connected to the ring while the hub node of the ring on the other end is connected to the edge node of the WAN, as shown in Figure 1.1. The design and management of metro networks are geared toward the different types of traffic streams and services streaming from the access network, and hence the topology can keep changing accordingly. We discuss this in Chapter 5.

The *backbone* segment of the network, which is invariably a mesh physical topology, spans from hundreds to thousands of kilometers, giving nationwide to

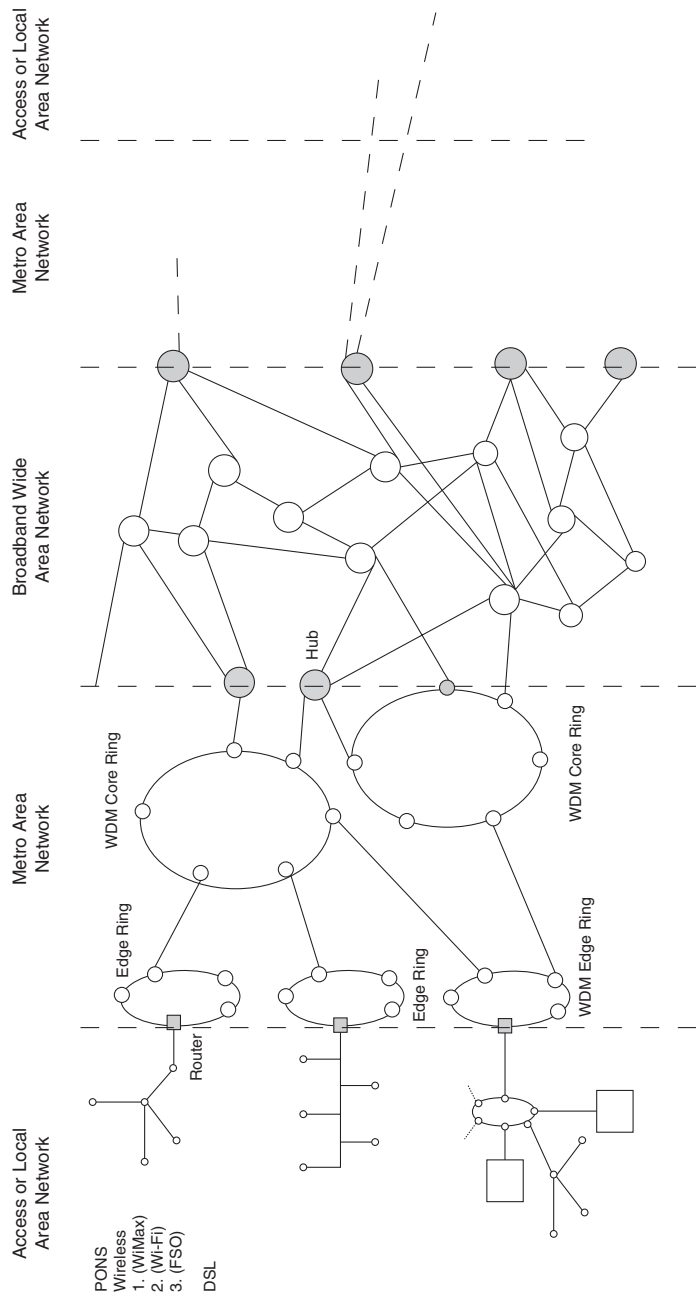


Figure 1.1 Classification of the communication network on the basis of reach.

global coverage, thus connecting the user in the access of LAN to another user or LAN in some other city, country, or continent. Backbone transport networks are shared among millions of users connected through the multiple metro-area networks. The long-haul core networks tend to be more stable in topology, unlike their metro counterpart. In core networks the emphasis is on high-bandwidth pipes and very high bit rate nodes so that more and more data are moved at high speed and efficiently. Traffic in the core network is transported between routers through high-speed gigabit links. The backbone routers use IP-over-SONET or IP-over-ATM-over-SONET technology to route IP (Internet Protocol) or the synchronous stream traffic over the wavelength channel fat pipes. Also, if the end user has large data, it can access the backbone network with a direct WDM channel. This is *optics in the access* with the access data over fiber. Chapter 6 is dedicated to the details of the optical wide area transport networks.

Optical networks could be classified in two generations: *first* and *second*. First-generation optical networks use optical fibers with WDM channels as a replacement for copper cables to increase transmission capacity. However, fiber deployment is mainly for point-to-point transmission. All the routing and switching functions are performed electronically at each node. Optical signals go through the optical to electrical conversion first for performing the switching and processing operation in the electronic domain. Later these electronic signals are reconverted to the optical domain for further transmission at each intermediate node as they propagate along an end-to-end path from one node to another. Figure 1.2a shows one such connection from source node “D” to destination node “B,” where the optical signal has to go through the O-E-O conversion at node 1, node 2, and node 3 in the transponders at each connection to the electronic node. The network nodes reach the electronic bottleneck as they are not able to process all the traffic carried by the node, which is in Tbps in WDM systems because of the limitation of the electronic processing speed. The node traffic includes not only the traffic which is intended for it but also the passing-by transit traffic intended for other destination nodes. Examples of first-generation network nodes are the SONET/SDH electronic switch, ATM switch, fiber data distribution interface (FDDI), etc. interconnected with fiber links for transmission. Figure 1.2b shows the schematic of a three-degree first-generation network node which is used in the network where the signal transmission is in the optical domain but at each node the optical signal goes through the optical-to-electronic and then again electronic-to-optical conversion before transmission to the next node.

To overcome the electronic bottleneck for high data speed, the *second-generation* optical networks have optical switching nodes instead of electronic switching nodes. These nodes have optical routing and switching functions and are capable of bypassing those signals that carry traffic not intended for the node directly in the optical domain. Hence, they are also called bypass nodes. With the availability of optical devices, such as optical add-drop multiplexers

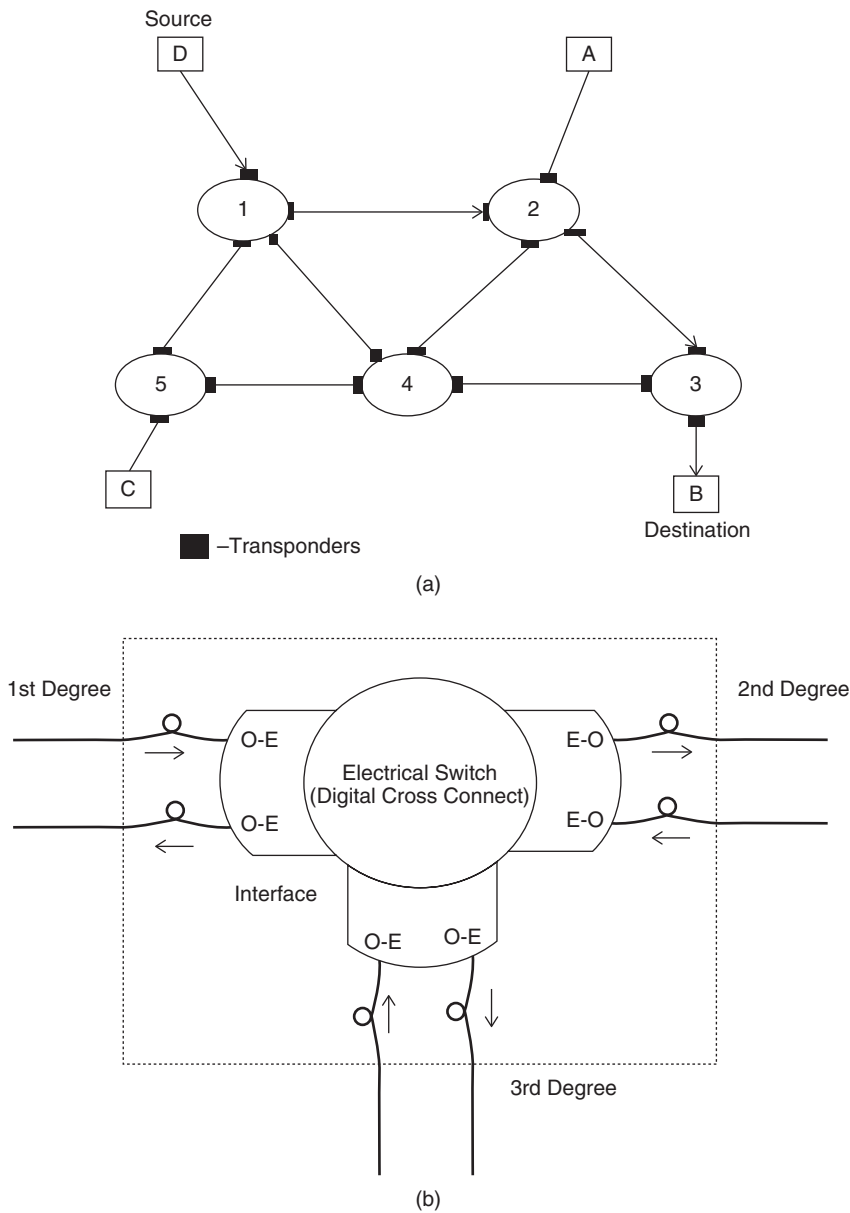


Figure 1.2 (a) First-generation optical network. (b) First-generation 3 degree node.

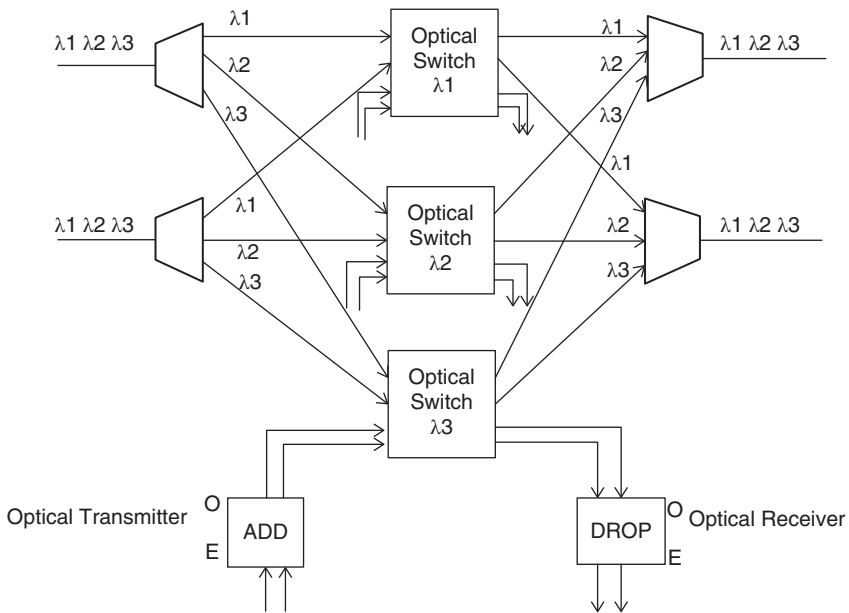


Figure 1.3 Optical bypass second-generation network node with add-drop ports.

(OADMs) and optical cross-connects (OXC)s, this has become possible. Figure 1.3 shows the optical bypass capability of the optical node. In this the traffic on the two input ports connected to the node can be bypassed without any O-E-O conversion to the two output ports. Any two nodes in this network can be directly connected together by a *wavelength (lightpath)* in a *single-hop* even if they are not connected directly with fiber. WDM optical technology is now widely deployed not only in WANs but also in MANs and LANs.

Two nodes, if not connected directly by a lightpath, can communicate also using a *multi-hop* approach, i.e. by using electronic switching at the intermediate nodes. This electronic switching can be provided by the electronic IP routers, or SONET equipment connected to the optical nodes, leading to an IP-over-WDM or a SONET-over-WDM network, respectively, in the hybrid network. These ports are also shown in Figure 1.3 as the add/drop ports.

1.2 Optical Networks: A Brief Picture

In the previous sections the optical networks were introduced. Next, we give a brief overview of the technologies, parameters, and some other details in order to understand them better in the subsequent chapters where they will be used and discussed in detail.

1.2.1 Multiplexing in Optical Networks

To use the large bandwidth of the fiber efficiently, signals of multiple connections have to be simultaneously transmitted over the fiber; in other words, multiplexing of signals has to be carried out without overlapping in the spectrum. This is employed for all *multi-user* communication in a *multi-access* environment. With the present technology, besides the time division multiplexing (TDM) in the electronic domain (Figure 1.4a), WDM is used in the optical domain on the existing fibers, as shown in Figure 1.4b. With WDM technology, multiple optical signals can be transmitted simultaneously and independently on orthogonal optical wavelength channels over a single fiber. Each of the channels has a rate of many gigabits/sec (Gbps), which significantly increases the usable bandwidth of an optical fiber. WDM systems with 88 WDM channels and bandwidth of 100 GHz per channel are now available. Thus, on a single fiber with both TDM and WDM schemes, a total traffic of $M(N \times b)$ bits/sec can be carried by wavelength multiplexing M wavelengths, with each wavelength time-multiplexing N data stream each of b bits/sec.

In addition to the increased usable bandwidth of an optical fiber, we exploit WDM for wavelength routing and switching and restoration in the optical domain. The other advantages of WDM are its reduced processing cost compared with electronic processing, data transparency, and efficient failure handling, as mentioned earlier. As a result, WDM has become a technology of choice in the optical networks. Further, within each WDM channel, it is

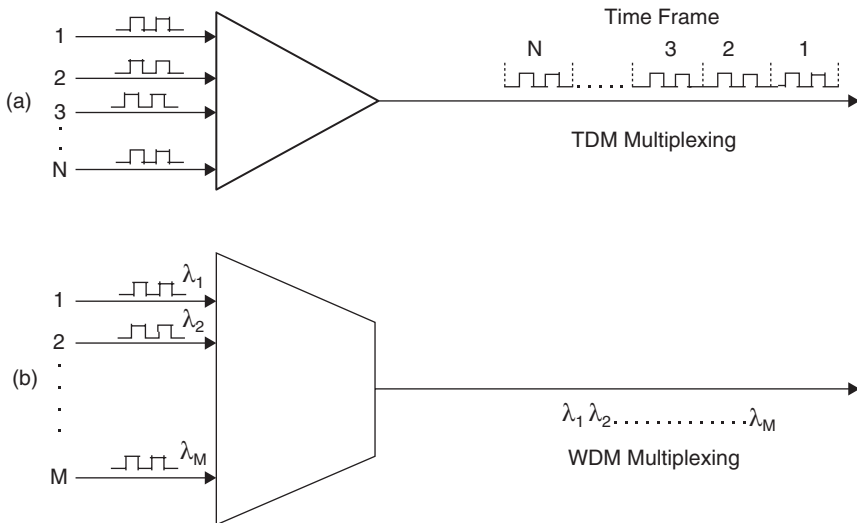


Figure 1.4 (a) Time division multiplexing. (b) Wavelength division multiplexing.

possible to have frequency division multiplexing (FDM) at the electronic level. In this case, the WDM channel bandwidth is subdivided into many radio frequency (RF) channels, each at a different frequency. Each radio frequency channel carries a different information signal. These RF channels are multiplexed to form a composite FDM signal and then the multiplexed signal intensity modulates the optical carrier. This is called *subcarrier multiplexing*. Optical code division multiplexing (OCDM) with code division multiplexing access (CDMA) is another optical multiplexing technique used in the networks. Optical time division multiplexing (OTDM) is also one of the possibilities for multi-user or multi-access technique to enhance the number of connections in the network, and is being actively researched to make it commercially viable.

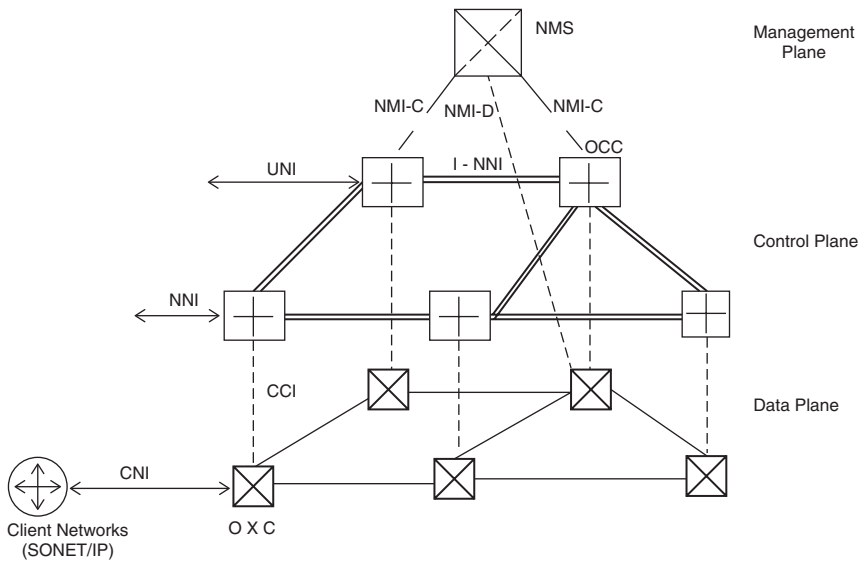
1.2.2 Services Supported by Optical Networks

Optical networks are required to support services which are diverse in geographical reach, applications, performance, and characteristics. The network may require connectivity in LANs, MANs, or WANs having a global reach. The optical network supports voice, multimedia, and data services. The services offered may vary in performance, with not so demanding email services (best effort) to high-capacity, secure, fast services of VoIP (voice over IP), IPTV (Internet Protocol television), telemedicine, or other highly secure financial services requiring very high performance in terms of having minimum or no errors and delay, and with high reliability of the network. All these different services have different requirements. But all the services are to be handled on a single underlying optical network by adaptively handling these with each special requirement for a large user population.

To handle the variety of traffic demands in a large network, the network functions can be broadly divided into three planes:

- *Transport plane.* The transport plane or data plane has the entire infrastructure, including the electronic switches and routers, the photonic transponders and OXCs, fiber links, etc. associated with the information/data transfer.
- *Control plane.* The control plane takes care of all the activities concerned with the connection provisioning, reconfiguration, performance, and fault management in the network.
- *Management plane.* This is the overarching plane which deals with the many and all operations of administration, maintenance, performance monitoring, fault diagnosis, statistics gathering, etc.

The network with the three functional planes is shown in Figure 1.5. We will be discussing the details of these planes in Chapter 7.



NMS : Network Management System
 OCC : Optical Connection Controller
 CCI : Connection Control Interface
 I-NNI : Internal Network Network Interface
 NMI-C : Network Management Interface - Control Plane
 NMI-D : Network Management Interface - Data Plane
 NNI : Network Network Interface
 UNI : User Network Interface
 CNI : Client Network Interface

Figure 1.5 Functional architecture of optical network.

1.2.3 WDM Optical Network Architectures

There are broadly three classes of WDM optical network architectures: broadcast-and-select (B&S) networks, wavelength routed networks (WRNs), and linear lightwave networks (LLNs).

1.2.3.1 Broadcast-and-Select Networks

A generic WDM broadcast-and-select network consists of a *passive optical star coupler* network node connecting the user nodes in the network. Each of these user nodes is equipped with one or more fixed or tunable optical transmitters and one or more fixed or tunable optical receivers. Different nodes can transmit messages on different wavelengths simultaneously. The star coupler combines all these messages and then *broadcasts* the combined message to all the nodes. A user node selects a designated wavelength to receive the desired message by tuning its receiver to that wavelength.

The *single-hop* B&S networks are *all-optical*; a message from the network user node once transmitted as light reaches its final destination directly, without being converted to electronic form in between. In order to support high data transmission in these networks we need to have optical transmitters and receivers at the nodes that can tune rapidly. The main networking challenge in these networks is the coordination of transmissions between the various user nodes connected to the central passive optical star coupler. In the absence of coordination or efficient medium access control protocol, collisions occur when two or more nodes transmit/receive on the same wavelength at the same time. To support fast switching efficiently in B&S networks, a *multi-hop* approach can be used, which avoids rapid tuning.

The advantage of B&S networks is in their simplicity and natural *multicast-ing* capability (ability to transmit a message to multiple destinations). However, they have limitations. First, they require a large number of wavelengths, typically at least as many as there are user network nodes in the network, because there is no *wavelength reuse* possible in the network. Thus, the networks are not scalable beyond the number of supported wavelengths. Second, they cannot span longer distances since the transmitted power is split among various nodes and each node receives only a small fraction of the transmitted power, which becomes smaller as the number of nodes increases. For these reasons, the main application for B&S is for high-speed local area and access networks. The other topologies which are used in these networks are the folded bus and the tree topology. We will be discussing the single-hop B&S networks in Chapter 3.

1.2.3.2 Wavelength Routed Networks

Wavelength routed WDM networks have the potential to avoid the three problems in the broadcast networks: the lack of wavelength reuse, power splitting loss, and scalability to WANs. A WRN consists of routing (or bypass) nodes interconnected by fiber links in an arbitrary mesh topology. The end user node is connected to a network node via a fiber link. Each end node is equipped with a set of optical transmitters and receivers for sending data into the network and receiving data from the network, respectively, both of which may be wavelength-tunable. In a WRN, a message can be sent from the source node to the destination node using a wavelength continuous route called a *lightpath* on one of the WDM channels, without requiring any O-E-O conversion and buffering at the intermediate nodes. This process is known as *wavelength routing*. The destination node of the lightpath accesses the network using receivers that are tuned to the wavelength on which the lightpath operates. A lightpath is an *all-optical communication path* between two nodes, established by allocating the same wavelength throughout the route of the transmitted data. Thus, it is a high-bandwidth pipe carrying data up to several gigabits per second, and is uniquely identified by a physical path and a

wavelength. The requirement that the same wavelength must be used on all the links along the selected route is known as the *wavelength continuity constraint*. Two lightpaths cannot be assigned the same wavelength on any single fiber. This requirement is known as *distinct wavelength assignment constraint*. However, two lightpaths can reuse the same wavelength if they use disjoint sets of links. This property is known as *wavelength reuse*. A WRN is illustrated in Figure 1.6.

The simultaneous transmission of messages on the same wavelength over fiber link disjoint paths or *wavelength reuse* property in WRNs makes them more scalable than B&S networks. Another important characteristic which enables WRNs to span long distances is that the transmitted power invested in the lightpath is not split and is sent to the relevant destination only. Given a WDM network, the problem of routing and assigning wavelengths to lightpaths is of paramount importance in these networks. Good algorithms are needed in order to ensure that functions of routing and wavelength assignment are performed using a minimum number of wavelengths. Connections in WRNs can be supported by using either a single-hop or a multi-hop approach. In the multi-hop approach, a packet from one node may have to be routed through some intermediate nodes with an O-E-O conversion before reaching its final destination. At these intermediate nodes, the packet is converted to electronic form and retransmitted on another wavelength. These attractive features – wavelength reuse, protocol transparency, and reliability – make WRNs suitable for WANs.

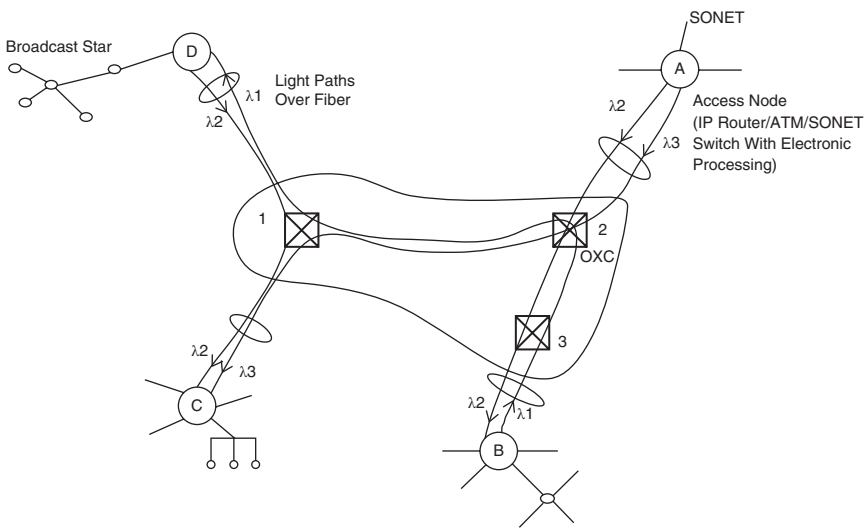


Figure 1.6 All-optical wavelength routing network architecture.

1.2.3.3 Linear Lightwave Networks

In the case of WRNs we multiplex several wavelengths and each of these orthogonal wavelengths can form a *lightpath* to route a connection in the network. In LLNs, meanwhile, we use *waveband*, which is a collection of a number of orthogonal wavelengths to route over the network as a unit. In these networks several wavebands are multiplexed on a fiber and several wavelengths are multiplexed in each waveband. The routing nodes de-multiplex and multiplex wavebands but not wavelengths within a waveband. Like the wavelength, the waveband-routed networks have the property that each waveband channel can be recognized in the optical network nodes (ONNs) and routed individually and hence network capacity can be improved with the spectrum reuse. Since an LLN node does not distinguish between wavelengths within a waveband, individual wavelengths within a waveband are separated from each other at the end node's optical receiver demultiplexer. The two constraints of *waveband continuity* and *distinct waveband assignment* as in WRN apply to LLNs. Further, there are two routing constraints unique to LLNs: *inseparability*, that is, channels belonging to the same waveband when combined on a single fiber cannot be separated within the network; and *distinct source combining*, that is, on any fiber, only signals from distinct sources may be combined. We will be limiting our discussion to wavelength routing networks and not considering the LLNs any further.

1.2.4 Services Types

The optical networks are used for different applications, varying from voice and data to other multimedia transmission. In general, network services for all the applications provided can be classified as follows:

- I) *Connection-oriented services*. These services are possible on circuit-switched networks, where the connection over the network is established before the traffic can be sent and is maintained until the connection is dropped. Examples of such services/protocols are the legacy telephone services, ATM, TCP (transmission control protocol), MPLS (multiple protocol label switching) services. All nodes have to maintain state information once the handshake procedure has been executed. Thus, QoS is maintained as decided by the service level agreement (SLA).

The connection-oriented services can have two types of connections:

- *Dedicated connections*. In the circuit-switched networks where the path is dedicated for a connection over long periods of time, possibly for months, days, or hours, it is said to be a dedicated connection. The user has a service agreement with the service provider for the connection. The connection is disrupted only when fault occurs and is then quickly put on another path.

- *Demand-oriented connections.* The demand-oriented connections are also circuit switched and provided to the user when demanded. As the network resources are shared, the services are provided on available free resources, otherwise the connection is blocked or dropped. Once the demand is accepted, the path is reserved and kept connected as demanded by the client. The demand may be over several seconds or milliseconds.

II) *Connectionless services.* Connectionless service does not require the establishment of any connection prior to sending data. The sender starts transmitting data to the destination according to the access control in use. Therefore, the connectionless services are less reliable than connection-oriented services. These are packet switched services; the connection is made as the data flows over the network, with IP providing the best effort (BE) services. They are much more economical but with reduced QoS compared with connection-oriented services.

1.2.5 Types of Traffic

- *Static and dynamic.* The traffic can be either fixed or changing dynamically with time, both in its source destination pair connection and in terms of demand size. In the case of static traffic demand, connection requests are known beforehand or a-priori with the estimation of long-term traffic demands of the network. This is expressed as the traffic matrix, which is static. In the case of dynamic traffic, the connection requests change with time in the network in random fashion and so does the traffic matrix.
- *Stream or synchronous traffic.* The stream traffic flow is uniform and constant and with the same clock period for every switch in the network – for example, SONET/SDH with fixed rate.
- *Asynchronous or random traffic.* The random traffic is dynamic with random arrival rate and length. It can take some probability distribution, i.e. uniform, Poisson, etc., or it may be bursty in nature, for example Internet traffic.

1.2.6 Switching Granularities

In optical networks we talk of different types of granularities, such as granularity of traffic, of switching speed, or of connection capacity.

Depending on the traffic demands of the various clients, optical networks need to be able to provide connections of different *traffic demand granularity*, such as 1 Gbps, 40 Gbps, etc. Also, the granularity of the connection's switching speed can be either fast or slow according to the required application and performance, QoS, etc. In the optical switching network, the switching can also be on the basis of granularity of connection capacity, such as whether it is space switching from one fiber to another, waveband switching, wavelength

switching, or time-slot switching. The connection capacity in space switching is of the order of Tbps, i.e. the total capacity of all the WDM channels in a fiber, while in the case of time-slot switching it is a single user connection, so the order of Mbps may be involved. The connections provided by optical switching networks must be able to adapt to time-varying network conditions and traffic requirements dynamically in order to optimize network performance and utilization of network resources.

1.2.6.1 Optical Circuit Switching

For the connection-oriented services in circuit switching we can perform switching at the following granularity:

- 1) *Space or fiber switching*. Any connection from one incoming fiber can be transferred to another outgoing fiber by switching in space. This is the coarsest level of switching in terms of granularity, as a large number of connections carrying a huge amount of data are switched in this case.
- 2) *Waveband switching*. This is the next level of lower switching in which a waveband is switched at the node. A waveband consists of a number of wavelengths. These wavebands are switched independently from each other – that is, network nodes are able to switch individual wavebands arriving on the same incoming fiber to a different waveband in the outgoing fiber.
- 3) *Wavelength switching*. This is a further finer granularity in which individual wavelengths in a waveband or a fiber itself are first de-multiplexed to the level of individual wavelengths, and then any of these wavelengths can be independently switched in the input fiber to the other wavelength in the output fiber.
- 4) *Sub-wavelength*. Sub-wavelength switching is also possible when OTDM is possible. Each slot in the TDM time frame carries single client data which can be switched to another slot. But this is still at the research stage. TDM in the electronic domain is done to multiplex lower rate data connections to accommodate low rate client data, as in SONET/SDH systems.

1.2.6.2 Packet Switching for Bursty Traffic

Circuit switching in optical networks is not economical in case of random traffic load. If the random bursty traffic is provided to a dedicated connection, then large bandwidth is wasted when low traffic density is greater than its statistical average. Also, on the contrary, the performance will deteriorate considerably when optical burst with high packet density arrives. In such situations switching is recommended for the random traffic by individual packet as it arrives at the switch. Packet switching is done at two granularity levels:

- 1) *Individual packet switching*. In the case of packet switching, each packet has a header with source-destination address which is recognized at the nodes.

After reading the address, a node forwards the packet to the next node on a wavelength channel. Thus, individual packets are switched independently from one to another node.

- 2) *Burst switching*. Unlike in the case of packet switching, packets are aggregated at the ingress node and sent as bursts across the network. For each burst a reservation control signal is sent on a dedicated control wavelength channel prior to sending the burst on one of the data wavelength channels after a pre-specified offset time.

1.3 Optical Network Layered Architecture

Until the early twentieth century before the fiber was well laid, only limited data traffic was carried over the existing telephone network which used to carry voice services. With optical fiber now the main transmission medium, the networks have become more data-centric rather than voice-centric, and digital transmission standards of higher bit rate, such as SDH/SONET, ATM, and IP networks, are well developed for this purpose. Internet Protocol is being used for transmitting all types of traffic, be it voice, video, or data, with all types of multimedia services on the optical fiber network. In other words, the services supported by the underlying optical network now are vast, extremely diverse in terms of connectivity, bandwidth, performance, reach, cost, and with many other features. Therefore, the network has to adapt to different special features for each type of service.

With the ubiquitous optical network to provide the variety of services mentioned above, the complexity of the network increases. Different components in the network have to perform a variety of functions. Therefore, as the OSI (open systems interconnection) model in computer networks, we can conceptually divide the functionalities of any node in the network in the constituent layers with client-server relations with the neighboring layers. The layered architecture allows flexibility not only in designing the equipment but also in design and implementation of the network. By employing a layered model, designers are left with enough leverage to add functions at each layer and to concentrate only on certain functions in the network provided by the specific layer while maintaining interoperability with other layers. The layered model helps in understanding and designing the optical network architecture, which is flexible, robust, and scalable.

In an optical network, when a user makes a request for connection, the source node makes a connection to its destination end by passing through a number of intermediate network elements or nodes. A variety of functions has to be carried out at each network element, such as framing of the packets, grooming, multiplexing, routing, and switching. In the layered architecture each layer carries out specific functions as required by the layer above it, then

the layer after performing the required functions, instructs the layer below to perform the necessary specified function. Thus the data flows between each layer. Each intermediate network element, between the source and the destination node along the path, has a certain number of layers depending on the network element's function, starting from the lowest layer up to a certain higher layer in the hierarchy.

In the seven-layered ISO (International Organization for Standardization) structure there are two types of layers: host and media. The upper four layers – the *transport*, *session*, *presentation*, and *applications* layers – are the *host layers* and the lower *media layer* has three sub-layers. These sub-layers are concerned with the functionalities of the data flow over the common network media. The lowest layer in the hierarchy is the *physical* layer, followed by the *data link* layer and the *network* layer. The physical layer provides the pipe with a certain bandwidth to the above layer. The pipe can be an optical fiber, a coaxial line, or any physical channel. The data link layer provides multiplexing, de-multiplexing of channels, framing of the data to be sent over the physical layer, etc. The network layer above the data link layer provides the end-to-end service to the message. In the present text we will be concentrating on these lowermost media layers in the optical networks.

The functional layered structure of a multilayered WDM optical network is shown in Figure 1.7. In the case of optical networks we have three layers for the functional layer abstraction: *client or user network*, *logical*, and *physical*. Each adjacent layer has a client server relationship with the lower layer serving the adjoining upper layer. The bottom layer, the physical layer, serves the adjoining

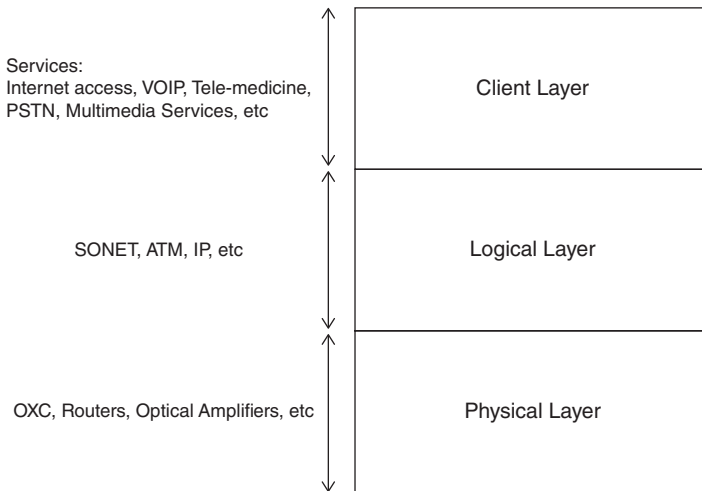


Figure 1.7 The multilayer optical network model.

second layer by providing the required basic optical channel bandwidth service to *logical network nodes* in the logical layer. As the physical layer is a fiber pipe, it therefore encompasses optical multiplexing, transport, and switching in the optical devices based on optical technology. The *logical switching nodes* (LSNs) of the logical layer, including IP routers, Ethernet switches, ATM switches, SONET/SDH switches, and OTN switches, are all based on electronic technology. The protocols associated with each of these switches do the formatting and partitioning of the data and move the data from source to destination over the optical physical layer by specific methods. Each of these LSNs organizes the raw offered capacity by the physical layer to the needs of the clients in the *user layer*, which is also called the *service* or *application layer*. The application layer includes all types of services, such as voice, video, and data. Thus, the several logical networks in the logical layer can provide a variety of specialized services to a connection demanded by the upper client layer.

For example, the SONET switches in the logical layer will electronically multiplex the low-speed data streams of the client layer into higher-speed streams, which in turn use optical wavelength channels provided by the physical layer to transmit the multiplexed data as an optical signal. The SONET channels can support a wide variety of services, such as telephone services, data, video, etc. In another case Internet services can be provided to some users through the IP layer sitting on the ATM over the SONET when reliability of ATM services is required before multiplexing them in the SONET layer. For certain IP we may have the IP layer directly over the optical physical layer, and yet in another case when the application layer connection requires a very high bandwidth, a raw *wavelength service* may directly be over the physical layer bypassing the logical layer, thus providing totally transparent optical network functions. Finally, in the physical layer, multiple wavelengths or lightpaths are optically multiplexed, switched, and routed in the WDM fiber physical layer, providing large bandwidth connectivity to the upper layers.

Next, we first give a simplistic view of how connection is made in an optical network before explaining in detail the functionalities of each layer. A typical optical network picture is given in Figure 1.8. The ONNs, which are OXC or wavelength or space switches, are interconnected with fibers in the physical optical layer. These ONNs are responsible for connecting different fibers as per the requirements of the logical connection demanded by the LSNs. These optical nodes are connected to the LSNs through the optical line terminal (OLT) or the network access terminal (NAT). NAT is a photonic device through which the electronic signal from the LSN is converted to the optical signal for onward transmission to the ONN, or vice versa. They are basically the transceivers. The LSN which can be either IP routers or the SONET/OTN switches are electronic. They are connected to the user equipment on one side and to the ONN on the other side through the NAT, thus they connect clients to the physical layer using a wavelength channel in the fiber.

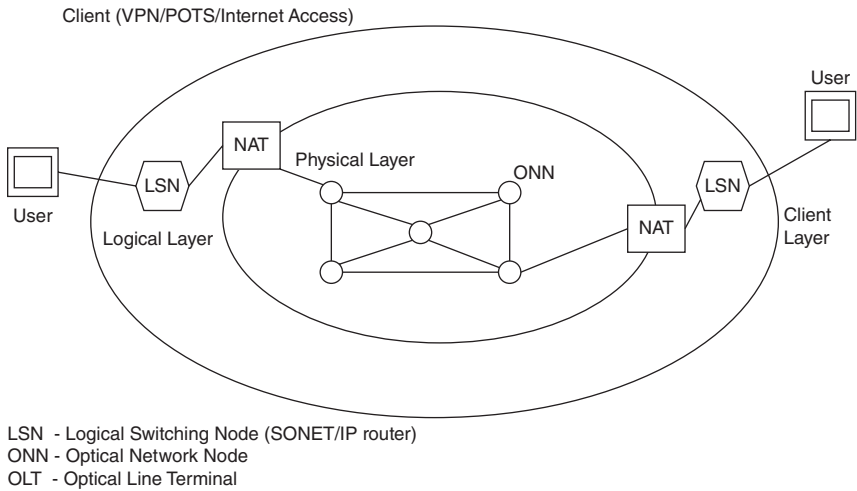


Figure 1.8 Schematic of an optical network.

The physical layer containing optical components, i.e. fiber, optical amplifiers, optical routers, etc., executes linear operations and is transparent to signal protocol, format, and bit rate, etc. The LSN in the logical layer has electronic components which can execute nonlinear operations on electronic signals and thus are dependent on the signal format, bit rate, etc. As optical technology advances in signal processing, it will be possible for the logical layer's nonlinear operational functions to be carried out in optical devices. At present, the transparent physical layer is considered to be almost linear and the logical layer, which is opaque, carries out all the nonlinear operations with electronic processing.

1.3.1 Layers and Sub-layers

Figure 1.9 illustrates details of the multilayered optical network functional layered structure, which gives the different functions of the physical and logical layers shown in Figure 1.8.

Physical layer. The functionality of the physical layer in an ONN, unlike from other communication networks, is divided into two sub layers: (a) the optical layer, and (b) the fiber layer.

- (a) **Optical layer.** The function of the optical layer is to provide lightpaths or λ -channel to carry the traffic of logical nodes in the upper logical layer, such as the SONET/SDH switches, IP/MPLS routers, as well as the electronic layer of the OTN. Thus, it can be viewed as the server layer to the upper logical layer that makes use of the services provided by the optical

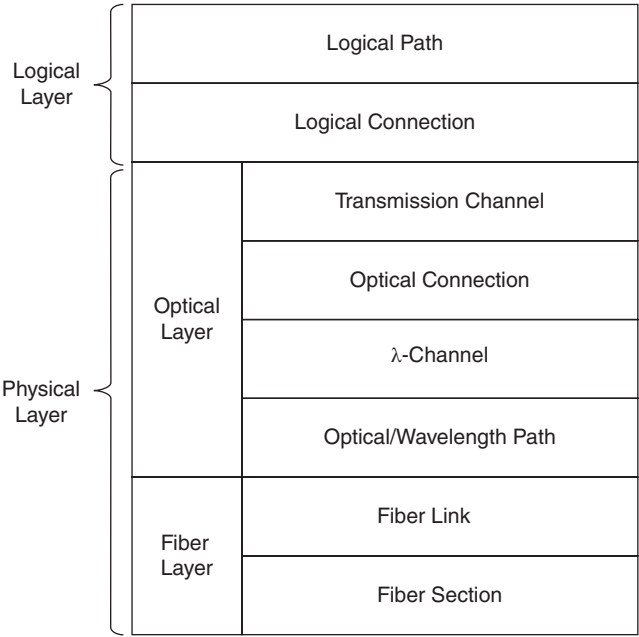


Figure 1.9 Layer/sub-layer structure of optical network connection.

layer to make a logical connection between the source-destination pair. The main features of such lightpath service of the optical layer are:

- The lightpath is set up and taken down as required by the logical layer.
- Typically the client layer specifies the bandwidth required to carry its connection traffic on the lightpath. The optical layer provisions the lightpath bandwidths as negotiated between the logical layer and the optical layer.
- An adaptation function may be required at the input and output interface of the optical and logical layer to convert user signals to signals that are compatible with the optical layer. The optical layer supports a specific range of signal types, bit rates, and protocols; these need to be established between the client and the optical layer.
- The lightpaths need to provide a guaranteed level of performance: bit error rate (BER), jitter, delay, etc.
- Multiple levels of services need to be supported for different connections: secured, unprotected, best-effort service, extensive fault management service connections, etc.
- Multicasting and broadcasting functions need to be supported.

Enabling the delivery of these services requires a *control and management* interface for the data plane supporting both ONNs and logical nodes. This

interface allows the LSNs to specify the set of *lightpaths* to be set up or taken down and sets the service parameters associated with the logical paths. Also it enables the optical layer to provide performance and fault management information to the logical layer. The management system communicates with the optical layer element management system (EMS) and the EMS in turn manages the optical layer. There is a hierarchical system: central network management system (NMS) and the distributed EMS. Signals from the NMS and EMS are transmitted through the distributed control network (DCN) to all the network elements. The details of these will be discussed further in Chapter 7.

Thus, to summarize, the functionalities of the optical layer cover all the aspects of optical connection, i.e. optical signal generation and transmission, optical multiplexing and routing, survivability, etc. The electro-optic network terminal (i.e. the NAT) provides the required interface between electronic end systems, the LSNs in the logical layer, and the ONNs in the optical layer through the access fiber. Each of these interface units is a transceiver with electro-optic devices, the laser and the photo-detector.

As the optical layer performs multiple functions, the functionalities of this layer can be further sub-divided in the following sub-layers, as shown in Figure 1.9:

- *Transmission channel.* The transmission channel in the optical layer carries out the adaptation function of converting the logical signal to transmission signal. The electro-optic conversion is carried out in the transmission processor, and on the receiver side the reverse operation of converting the optical signal to an electrical signal is done in the receive processor. The other functions carried out in these processors are the modulation/de-modulation, multiplexing/de-multiplexing, coding/decoding, and other functions to adapt well to the optical topological connections and vice versa before the signals are converted to optical/electronic format by the optical transmitter/optical receiver, respectively, in the network interface unit at the source and destination.
- *Optical connection.* The function of the optical connection sub-layer is to provide the end-to-end optical communication channel between the two terminating transceiver pairs at the access interface unit in the optical layer. The terminating interface units tune their transceivers to the assigned wavelength of the λ -channel. The λ -channel is the basic information unit carrier in the physical layer and is independently routed and switched by the ONNs to establish the optical connection.
- *λ -channel.* In a WDM system, λ -channels are the smallest granularity in the optical spectrum partitioning, each having a distinct wavelength to carry the information. Several lower bit rate signals of the logical channel are time division multiplexed on a single λ -channel. The λ -channels can be switched at the nodes (OXC) to different paths at the nodes. Thus,

λ -channels can be multiplexed (WDM), access (WDMA – wavelength division multiple access), and switched as an identity at the nodes.

- *Optical path*: This sub-layer manages the optical connection from source to destination through sequences of optical nodes (OXC) on a selected wavelength λ -channel.

(b) *Fiber layer*. The fiber layer takes care of the optical infrastructure aspects. Its functionality is divided into two sub-layers:

- *Fiber link*. The fiber links or inter-nodal hop between the ONNs along the optical path are the fiber link layer.
- *Fiber section*. The fiber sections between the amplification sections are managed by the fiber section sub-layer.

Logical layer. The logical layer above the physical layer has its functionality in providing the virtual unidirectional connections between the pair of end systems in the client layer external ports. This connection is provided with the help of a pair of source and destination NATs, discussed in the optical layer, at the interface of the physical and logical layers. The logical layer functionalities can be further divided into two sub-layers:

- *Logical connection*. The logical connection carries electronic signals in a particular format as required by the end system – for example, it may be an ATM cell, IP packet, analog video, or SONET digital bit stream. These logical connections are carried by an optical connection with the resources of the physical layer. The logical connection is carried over the optical connection through the *transmission channels*. The transmission channel has the adaptation function of converting the logical signal to an optical transmission signal.
- *Logical path layer*. The virtual connection provides the end-to-end connection between the pair of end systems. It is carried on the logical path layer with the help of one or multiple logical hops or connections made with the LSNs.

The multi-layered architecture thus breaks down the different functions, such as multiplexing, switching, grooming, O-E-O conversion, routing, of the complex optical network into separate layers and thus these can then be handled with ease. The number of sub layers in different networks and their devices will differ from one to another depending on the size, topology, and functions involved for making connections. For a long link length in a WAN, all the sub layers will be present, while in the case of link between any two nodes in the MAN or LAN, the sub layer structure will be somewhat simpler because of lesser functions which have to be performed by the nodes of the link in these cases.

1.4 Organization of the Book

In Chapter 1, optical networks were summarized in order to give an overview of the different categories of the optical networks, their working and parameters, and the terminologies which are generally used. Chapter 2 deals with building blocks of the optical networks. With an overview of the enabling infrastructure in the physical layer of the optical network, the chapter gives details of the network photonic and optical switching devices used in the current WDM networks. For more comprehensive details of fibers and their characteristics, lasers, photo-detectors, and the different optical amplifiers used in the optical networks, readers are encouraged to turn to the dedicated literature on these topics [5–15]. Chapter 3, on single-hop B&S networks used in access networks and for LANs, looks in detail at topologies, media access control (MAC) protocols, and other specifics. Also discussed in this chapter are basic concepts of traffic types in optical network topologies which are more generic. Chapter 4 examines the various access networks, their limitations, and the available high-bandwidth PONs with their newer avatars.

The metro area networks discussed in Chapter 5 examine the SONET and OTN protocols, etc. The wavelength routed WANs are dealt with in Chapter 6. This chapter examines the wavelength routing and assignment (RWA) problem, the logical topology design issues, and the concept of integer linear programming (ILP) and heuristic solutions of these networks.

With an overview about the NMS in Chapter 1, Chapter 7 discusses in detail the very important topic of network management, control, and signaling to make the network work with details of GMPLS (generalized multi-protocol label switching). In Chapter 8, impairment awareness and survivability, protection, and restoration are covered in detail, consistent with the growing importance of optical layer fault management in networks. The chapter considers the very important issue of optical network impairments and survivability and how they are taken into account while designing networks.

There is a need for the optical layer to have low cost, flexibility, and reconfigurability instead of the present fixed nature in order to be geared up to accommodate the varying traffic demands and services. The present dense wavelength division multiplexing (DWDM) networks based on ITU-T split the useful fiber spectrum into fixed 50 GHz and 100 GHz spectrum slots. The optical devices and switches in use are still not fully flexible and therefore the network does not have the flexibility to adjust itself to the traffic demands. Addressing the need for the optical networks to evolve in this direction, the last two chapters of the book, Chapters 9 and 10, are devoted to the topics of elastic optical networks (EONs) and SDON.

1.5 Summary

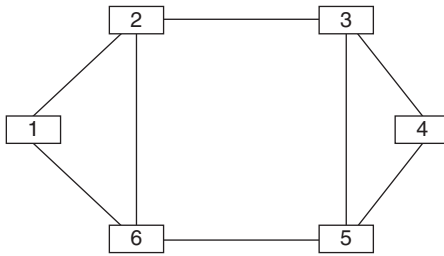
In this introductory chapter we first talked of the present-day demand of communication traffic and the need for an optical fiber network to meet the high-bandwidth, large area network to support all types of new and flexible services.

The networks were classified in terms of geographical reach: the LAN, MAN, and the WAN, and the two generations. The first-generation WDM networks use optical fiber as a replacement for copper cable to get higher capacities, and the second-generation networks use the other characteristics of the fiber to provide circuit-switched lightpaths by routing and switching wavelengths inside the network.

The chapter gives a brief overview of the second-generation optical networks in order to make the subject easier to understand in subsequent chapters where these topics will be discussed in detail. The different network architectures, traffic types, connections, services, types of switching, and the network layered abstractions are introduced.

Problems

- 1.1 (a) What factors limit the scalability and throughput of the B&S and the WRN networks?
- (b) Figure 1.9 gives the layered structure for a multi-wavelength hybrid optical network connection. Draw a similar layered structure for a transparent multi-wavelength B&S and a transparent all-optical WRN connection.
- (c) What is the bandwidth in THz of the signal at 1300 nm wavelength for a 150 nm spectrum?
- (d) What do you understand by “electronic bottleneck”? What is the way to eliminate it?
- (e) What is the difference between “FDM” and “WDM”?
- 1.2 In a 640 km 1st generation link 40 Gbps data is transmitted using 16 separate fiber pairs. Calculate the number of regenerators required if they are placed every 120 km. If, instead, a 16-channel WDM system is used for the above link with one fiber pair only, how many optical amplifiers with a gain of 30 dB each will be required if the amplifiers are placed every 80 km and a regenerator required only after 320 km. Compare the regenerators required in the two cases.
- 1.3 For the six-node mesh wavelength-routed optical WDM network given in Figure 1.10, connections 1–4 and 2–6 are on wavelength λ_1 , and on



wavelength λ_2 , respectively. Establish the connections 2–4 and 3–6 using the minimum number of wavelengths with no wavelength conversion available at any node.

- 1.4 If the six-node network was connected in a passive star topology, how will the above connections be made with minimum number of wavelengths?
- 1.5 What type of service; dedicated or demand connection-oriented *circuit switched* or connectionless *packet switched*, should be provided to the following services:
 - (a) VoIP
 - (b) IPTV
 - (c) telemedicine
 - (d) highly secure financial service
 - (e) social networking
- 1.6 All the above services are provided by the same underlying core fiber network. Explain how it is possible to give such diverse services using one network.

References

- 1 Goransson, P. and Black, C. (2014). *Software Defined Networks: A Comprehensive Approach*. Morgan Kaufmann.
- 2 Lopez, V. and Velasco, L. (2016). *Elastic Optical Networks: Architectures, Technologies, and Control*. Springer International Publishing.
- 3 Kreutz, D., Ramos, F.M.V., Verissimo, P. et al. (2015). Software-defined networking: a comprehensive survey. *Proc. IEEE* 103 (1): 14–76.
- 4 Thyagaturu, A.S., Mercian, A., McGarry, M.P. et al. (2016). Software defined optical networks (SDONs): a comprehensive survey. *IEEE Commun. Surv. Tutorials* 18 (4): 2738–2786.

- 5 Okamoto, K. (2006). *Fundamentals of Optical Waveguides*, 2e. New York: Academic.
- 6 Buck, J.A. (2004). *Fundamentals of Optical Fibers*, 2e. Hoboken, NJ: Wiley.
- 7 Fukuda, M. (1999). *Optical Semiconductor Devices*. Hoboken, NJ: Wiley.
- 8 Neamen, D.A. (2006). *An Introduction to Semiconductor Devices*. New York: McGraw-Hill.
- 9 Personick, S.D. (1973). Receiver design for digital fiber communication systems. *Bell Syst. Technol. J.* 52: 843–886.
- 10 Schneider, K. and Zimmermann, H.K. (2006). *Highly Sensitive Optical Receivers*. New York: Springer.
- 11 Desurvire, E. (2002). *Erbium-Doped Fiber Amplifiers: Principles and Applications*. New York: Wiley.
- 12 Yariv, A. and Yeh, P. (2006). *Photonics: Optical Electronics in Modern Communications*. New York: Oxford University Press.
- 13 Islam, M.N. (ed.) (2004). *Raman Amplifiers for Telecommunications 1 – Physical Principles*. New York: Springer.
- 14 Islam, M.N. (ed.) (2004). *Raman Amplifiers for Telecommunications 2 – Sub-Systems and Systems*. New York: Springer.
- 15 O'Mahoney, M.J. (1988). Semiconductor laser optical amplifiers for use in future fiber systems. *J. Lightwave Technol.* 6: 531–544.