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Optical networking technology

Technological advances in semiconductor products have essentially been the primary driver for the growth of networking that led to improvements and simplification in the long-distance communication infrastructure in the twentieth century. Two major networks of networks, the public switched telephone network (PSTN) and the Internet and Internet II, exist today. The PSTN, a low-delay, fixed-bandwidth network of networks based on the circuit switching principle, provides a very high quality of service (QoS) for large-scale, advanced voice services. The Internet provides very flexible data services such as e-mail and access to the World Wide Web. Packet-switched internet protocol (IP) networks are replacing the electronic-switched, connection-oriented networks of the past century. For example, the Internet is primarily based on packet switching. It is a variable-delay, variable-bandwidth network that provides no guarantee on the quality of service in its initial phase. However, the Internet traffic volume has grown considerably over the last decade. Data traffic now exceeds voice traffic. Various methods have evolved to provide high levels of QoS on packet networks – particularly for voice and other real-time services. Further advances in the area of telecommunications over the last half a century have enabled the communication networks to see the *light*. Over the 1980s and 1990s, research into optical fibers and their applications in networking revolutionized the communications industry. Current telecommunication transmission lines employ light signals to carry data over guided channels, called *optical fibers*. The transmission of signals that travel at the speed of light is not new and has been in existence in the form of radio broadcasts for several decades. However, such a transmission technology over a guided medium, unlike air, with very low attenuation and bit-error rates makes optical fibers a natural choice for the medium of communication for next-generation high-speed networks. The first major change with the development of the fiber technology was to replace copper wires by fibers. This change brought high reliability in data transmission, improved the signal-to-noise ratio and reduced bit-error rates.

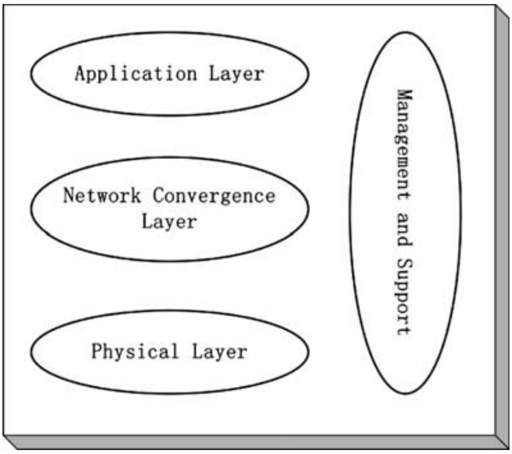

Fig. 1.1. A next-generation network architecture.

With the advent of optical transmission technology over optical fibers, the communication networks have attained an orders of magnitude increase in the network capacity. This development had a tremendous and dramatic impact on social and economic aspects of the lives of people around the world [1, 3, 4, 5]. With increasing data traffic and high QoS requirements on packet networks, it is becoming desirable to bring together various different networks around a single packet-based core network. The *next-generation network (NGI) architectures* are converging to share a common high-level architecture as shown in Fig. 1.1. It would integrate multiple different networks, e.g., PSTN, IP, ATM (asynchronous transmission mode), and SONET (synchronous optical networks)/SDH (synchronous digital hierarchy), etc. based networks into a single framework.

Initially, the migration from electronic to optical transmission technology was achieved by only replacing copper cables with optical fibers. Traditional time-division multiplexing (TDM) that allows multiple users to share the bandwidth of a link was employed. In TDM, the bandwidth sharing is in the time domain. Multiplexing techniques specific to optical transmission technology were not employed in the early networks. The synchronous optical network is the most popular network in this category. SONET is based on a ring-architecture, employing circuit-switched connections to carry voice and data traffic. The second-generation optical network uses wavelength-division multiplexing (WDM) which is similar to frequency-division multiplexing (FDM).

1.1 Wavelength-division multiplexing

The optical transport layer is capable of delivering multi-gigabit bandwidth with high reliability to the service platforms. The bandwidth available on a fiber is

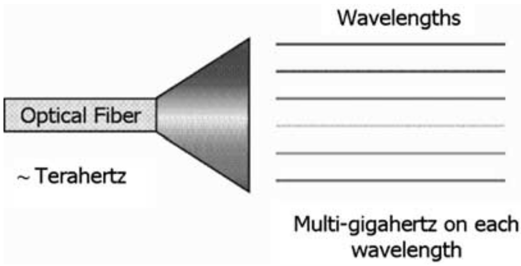

Fig. 1.2. A fiber divided among multiple wavelengths.

approximately 50 THz (terahertz). Increasing the transmission rates could not be adopted as the only means of increasing the network capacity. Transmission rates beyond a few tens of gigabits per second could not be sustained for longer distances for reasons of impairments due to amplifiers, dispersion, non-linear effects of fiber, and cross-talk. Hence, wavelength-division multiplexing was introduced, which divided the available fiber bandwidth into multiple smaller bandwidth units called *wavelengths*.

The WDM-based networking concept was derived from a vision of accessing a larger fraction of the approximately 50 THz theoretical information bandwidth of a single-mode fiber. A natural approach to utilizing the fiber bandwidth efficiently is to partition the usable bandwidth into non-overlapping wavelength bands. Each wavelength, operating at several gigabits per second, is used at the electronic speed of the end-users. The end-stations thus can communicate using wavelength-level network interfaces. Wavelength-division multiplexing turns out to be the most promising candidate for improving fiber bandwidth utilization in future optical networks. Figure 1.2 depicts the WDM view of a fiber link. The research, development, and deployment of the WDM technology evolved at a rapid pace to fulfill the increasing bandwidth requirement and deploy new network services.

The wavelength-division multiplexing mechanism divides the bandwidth *space* into smaller portions. Hence, the multiplexing is said to occur in the space domain. Different connections, each between a single source–destination pair, can share the available bandwidth on a link using different wavelength channels. Advanced features such as optical channel routing and switching supports flexible, scalable, and reliable transport of a wide variety of client signals at ultra-high speed. This next-generation network concept dramatically increases, and maximally shares, the backbone network infrastructure capacity and provides sophisticated service differentiation for emerging data applications. Transport networking enables the service layer to operate more effectively, freeing it from the constraints of physical topology to focus on the sufficiently large challenge of meeting the service requirements.

The application signals have widely varying characteristics, e.g., signal format, type of signal, and transmission speed. To transport the varied application signals

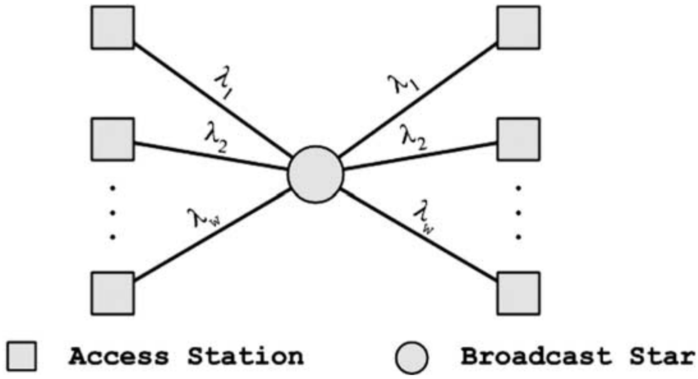

Fig. 1.3. A broadcast-and-select network.

over the optical transport network, a network service layer is needed to map the signals to optical channel signals along with an associated "overhead" to ensure proper networking functions. This layer, for example, captures today's IP and ATM capabilities with statistical multiplexing and a QoS guarantee. Protocols such as multi-protocol label switching (MPLS), resource reservation protocol (RSVP), and differentiated services (DiffServ) play a major role in supporting the required QoS across a wide set of applications. The network service layer relies entirely on the transport layer for the delivery of multi-gigabit bandwidth where and when it is needed to connect to its peers.

1.2 Broadcast-and-select networks

Early optical networks employed broadcast-and-select technology. In such networks, each node that needs to transmit data broadcasts it using a single wavelength and the receiving node selects the information it wants to receive by tuning its receiver to that wavelength. In a WDM network, many nodes may transmit simultaneously, each using a different wavelength on the same fiber or passing through the same node. A broadcast star architecture as shown in Fig. 1.3 is an example of such a network.

Nodes in the broadcast-and-select networks are connected by links and optical couplers. An optical coupler is a *passive* component that is used for either combining or splitting the signals into or from a fiber. The couplers can be configured to split/combine signals in specific ratios so as to achieve a proper energy mix/split. The central coupler in Fig. 1.3 couples all of the energy transmitted by all nodes and splits the combined energy equally among all receivers.

It should be evident that the data transmitted by a node is received by all other nodes. Every node only uses the data that is destined for it and discards the rest.

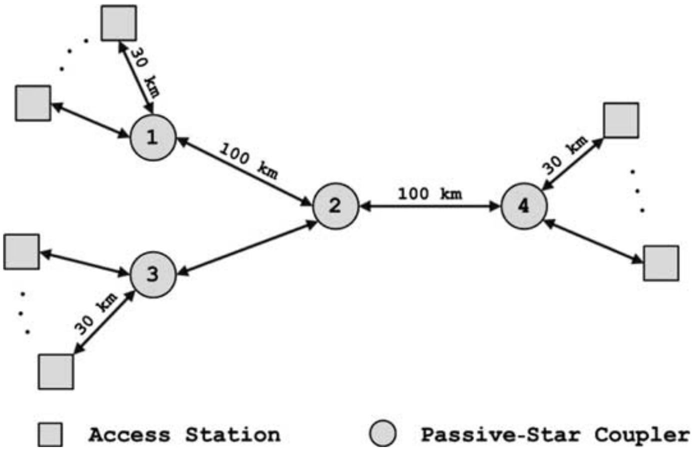

Fig. 1.4. A combination of broadcast-and-select elements used to form a network.

The major features of optical couplers include low insertion loss, excellent environmental stability, long-term reliability, and multiple performance levels. Such networks are typically found in local area networks and cable-TV or video distribution networks, networks that typically provide the end-user connectivity. Different receiving nodes can tune their receiver to different wavelength channels and receive the information pertinent to it from the appropriate source node.

Several broadcast star nodes can be used to design a broadcast-star network. A bigger network that employs several broadcast stars is shown in Fig. 1.4. In this network, the coupling nodes, marked as nodes 1 to 4, couple the energy received from all incoming fibers and redistribute it to all outgoing fibers. Only a single pair of two end nodes that wish to communicate can use one wavelength in a one-to-one communication setup. Thus if there are W wavelengths in the system, only W access node-pairs can communicate (W transmitter and W receivers) irrespective of the size of the network. Moreover, a centralized arbiter must control the wavelength usage. The last two items are the reason why such a network cannot be used in wide area networks or bigger network applications. In the case of a multicasting application, data transmitted from one node can be received by more than one node without any extra effort.

1.2.1 Broadcast-and-select network design

In order for a source node to communicate with a receiver, both nodes must be operating at the same wavelength. One way to organize nodes in the broadcast-and-select networks is to have each node transmit data on a specific wavelength. A network with N nodes would employ W wavelengths where every node is assigned a single wavelength to transmit. A unique wavelength can be assigned to every node to transmit if $N \leq W$. Otherwise many transmitting nodes will have to share a wavelength. If $W < N$ then a control mechanism would also be required to decide which transmitting station among the many that share the wavelength would use the channel at a given time. A channel access protocol governs the sharing. There are several ways to design a broadcast-and-select network with each transmitting and receiving node being equipped with a different number of transmitters and receivers. They are listed below.

(i) A fixed transmitter and single tunable receiver.
(ii) A fixed transmitter and W receivers.
(iii) W transmitters and a single fixed receiver.
(iv) $1 < k_1 < W$ tunable transmitters and $1 < k_2 < W$ tunable receivers.

Different schemes will require a different mechanism to control the network. For example, with a single transmitter and W receivers at a node, a node can transmit at any time as long as the wavelength is free and the central controller only assigns the transmission time to a node so that there is no collision. This is called a fixed transmitter scheme. A similar control is exercised in the third case, where the receive time needs to be allocated for a node along with the condition that the wavelength used by the receiver must be free for that duration. In the last case control is more complicated and various control mechanisms can be derived. Several schemes to control such a system have been developed in the literature.

Each receiver node may have one or more receivers that can be tuned to the wavelength of the transmitting station that is the current source of data to that particular node. This is called a tunable receiver scheme. In this environment, a control channel is used to establish a connection between source and destination nodes to allow the latter to tune their receivers to the transmitting wavelength of the source nodes. Quite a bit of time is lost in deciding who should transmit to whom and in tuning the receivers. The control channel may also be time slotted where data and control are separated. In a control round, each transmitting station requests the possible desired destination for which it has some data. The destination nodes arbitrate and decide on their respective current sources and correspondingly tune their receivers to the wavelengths of the transmitting nodes. The actual data is then transmitted. On the other hand, control could be asynchronous in which a transmitting station sends a request to the destination node and upon receiving an acknowledgement, transmits the data. An acknowledgement is sent in such a way that a tuning period is allowed at the destination node. The actual transmission only occurs after the tuning is complete.

In the case where the receiving node has W receivers, receiver arbitration is not required. Transmitter arbitration is still required irrespective of whether $N > W$

or $N < W$, to decide which node should transmit at a given time to a particular receiver since more than one node may have data to transmit.

In an alternate scenario, each receiver may have a fixed-wavelength receiver. This is called a fixed receiver scheme. In this case, a transmitting node has to tune to the wavelength of the receiver before transmitting. This is called a tunable transmitter scheme.

In the case where the sender node has W transmitters, the sender can transmit on the receiver's wavelength without arbitration. However, a control mechanism is required to decide which node should transmit to the destination at a given time. Again the control mechanism can be synchronous or asynchronous.

In another scenario the tuning of both transmitters and receivers to match the transmitter–receiver pairs using a control mechanism may be deployed.

The disadvantage of such a passive network is that its range is limited. Long-range networks, typically countrywide networks, cannot employ such a broadcast-and-select mechanism due to capacity inefficiency. The data is unnecessarily sent to all the nodes in the network, resulting in poor network utilization. Also, as the signals travel farther the quality of the signal degrades necessitating signal regeneration with reshaping and retiming.

1.3 Wavelength-routed WDM networks

In order to avoid unnecessary transmission of signals to nodes that do not require them, *wavelength routing* mechanisms were developed and deployed. A wide variety of optical components to build WDM networks were developed that included wide-band optical amplifiers (OAs), optical add/drop multiplexers (OADMs), and optical cross-connects (OXCs). Thus it became possible to route data to their respective destinations based on their wavelengths. All-optical networks employing wavelength-division multiplexing and wavelength routing are now viable solutions for wide area networks (WANs) and metropolitan area networks (MANs).

The use of wavelength to route data is referred to as wavelength routing, and networks that employ this technique are known as *wavelength-routed* networks [234, 236, 240]. In such networks, each connection between a pair of nodes is assigned a path and a unique wavelength through the network. A connection from one node to another node, established on a particular wavelength, is referred to as a *lightpath*. Connections with paths that share a common link in the network are assigned different wavelengths. The two end nodes may use any protocol and signal type such as analog or digital to modulate the optical signal. These wavelength-routed WDM networks thus offer the advantages of protocol transparency and simplified management and processing in comparison to routing in telecommunications systems using digital cross-connects.

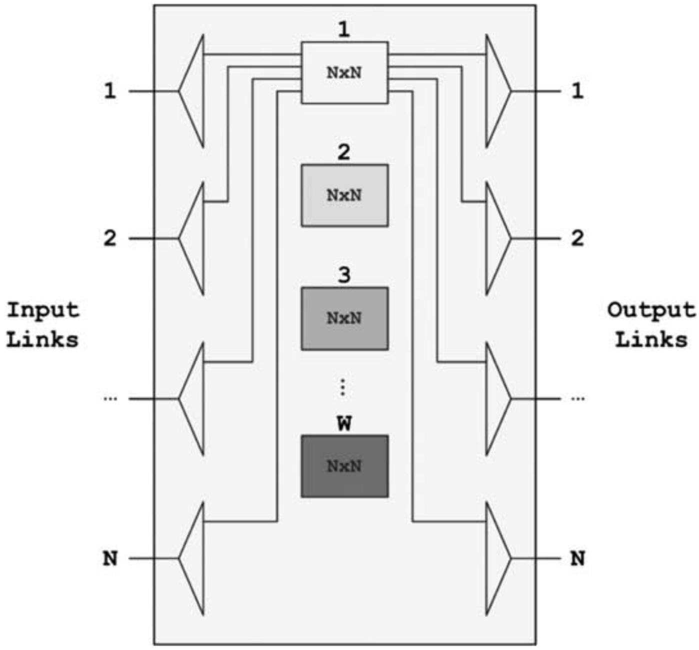

Fig. 1.5. Node architecture in a wavelength-routed WDM network without wavelength conversion.

In wavelength-routed networks the nodes employ *optical cross-connects* that can switch an individual wavelength from one link to another. In order to operate the network in a transparent manner, the switching of a wavelength is done in the optical domain. Figure 1.5 depicts an optical switching node. In this architecture, wavelengths on an incoming fiber are demultiplexed and separated. Then the same wavelengths from all fibers are switched together and routed to the outgoing fibers using a wavelength switching mechanism. There is a separate switch for each wavelength. At the output, all wavelengths being routed to one fiber are multiplexed and then sent out to the outgoing fiber.

A wavelength-routed WDM network is shown in Fig. 1.6. The figure shows connections established between nodes A and C, H to G, B to F, and D and E. The connections from nodes A to C and B to F share a link. Hence, they have to use different wavelengths on the fiber.

In a wavelength-routed WDM network, the path of a signal is determined by the location of the signal transmitter, the wavelength on which it is transmitted, and the state of the network devices. An example of such a network with two wavelengths on each link is shown in Fig. 1.7. There are two connections that are in progress, one from node 1 to node 2 using wavelength λ_1, and another from

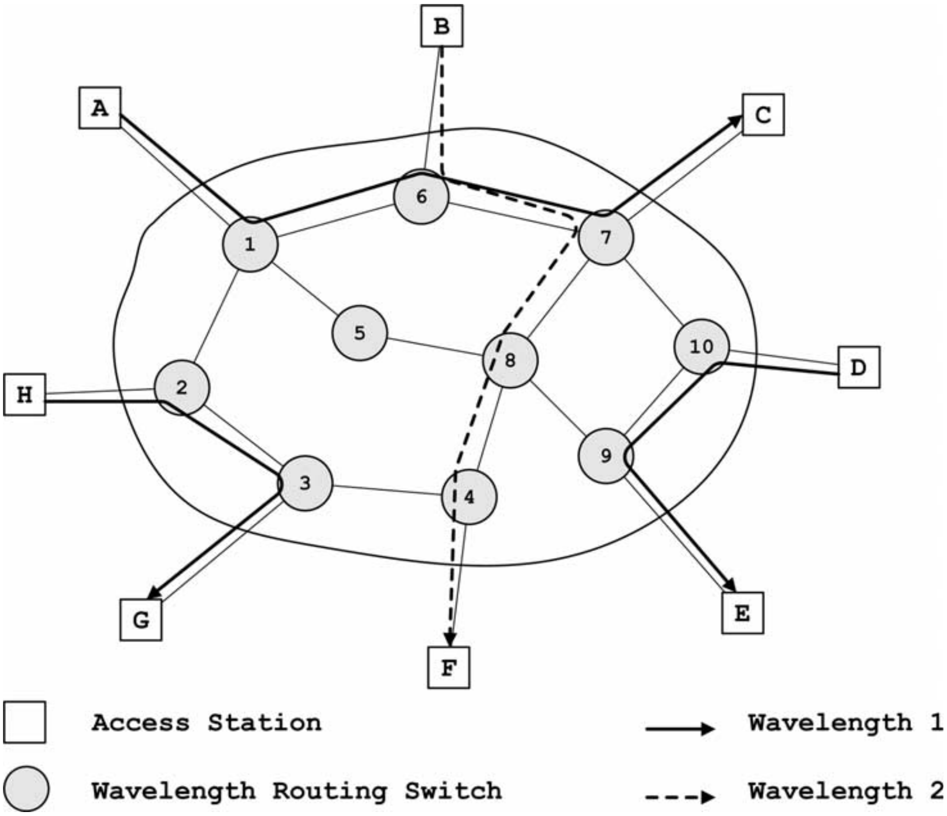

Fig. 1.6. A wavelength-routed WDM network.

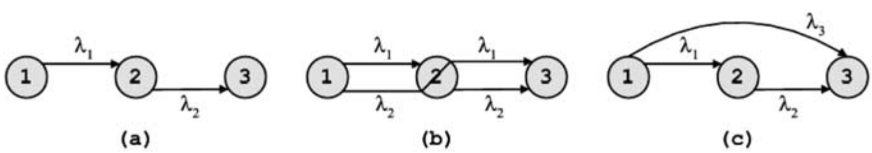

Fig. 1.7. A demonstration for the wavelength continuity constraint on a two-hop path.

node 2 to node 3 using wavelength λ_2. A connection request from node 1 to node 3 is blocked, although free wavelengths are available on both link 1 and link 2. This is because of the *wavelength continuity constraint*, that is, the same wavelength must be assigned to a connection on every link. Otherwise a wavelength converter is required at the switching node 2. Connection requests to set up lightpaths encounter a higher blocking probability than path setup requests do in electronic-switched networks because of the wavelength continuity constraint.

1.4 Wavelength conversion in WDM networks

As noted above in optical networks, the *wavelength continuity constraint* restricts a connection to occupy the same wavelength on every link of a chosen path from source to destination. The transmission of signals on the fiber has to follow certain restrictions due to the technological constraints. The wavelength continuity constraint could result in rejecting a call even though the required capacity is available on all the links of the path but not on the same wavelength. The reason for rejecting a request is due to the inability of intermediate nodes to switch the connection from one wavelength to another on two consecutive links. The wavelength continuity constraint and the need for conversion are demonstrated in Fig. 1.7.

The effect of wavelength conversion is analyzed using different models. Initially analytical models to evaluate the performance of wavelength-routed WDM networks were developed using the assumption that the link loads were statistically independent [10, 179, 180]. This assumption is justified based on the overall effect of routing various connections and the intermixing of traffic over different links. Thus the traffic on a link appeared to be independent of other links in the network. Analytical models for quantifying the benefits of employing wavelength conversion capabilities in a network were later developed [87, 164, 179, 197, 219, 267, 269, 270, 272, 279], continuing with the same assumption of statistical link load independence. The concept of link load correlation was put forward in later analysis [268].

Wavelength converters are also expensive devices. Thus another expectation in network design has been that either not every node can perform wavelength conversion or a node cannot convert any wavelength arbitrarily to any other wavelength. The former concept is named sparse-wavelength conversion, where only a few nodes in the network have full-wavelength conversion capability. The latter concept is called limited-wavelength conversion, where a wavelength may only be translated to some limited set of wavelengths at a node. A model for analyzing the network performance in terms of the blocking probability with sparse-wavelength conversion with link load correlation has been developed in [268]. Models for limited-range wavelength conversion can be found in [144, 235, 287, 294].

An alternative for wavelength conversion is a multiple-fiber network where each link consist of multiple fibers, say F. Thus every wavelength is available on every link F times. Analytical models for multi-fiber networks were developed by extending the models for a single-fiber wavelength-routed network [196].

Most of the analytical models assume fixed-path routing, i.e. the path that is chosen for establishing a connection from the source to the destination is known a priori. Analytical models that account for dynamic routing based on up-to-date network status are complex, and hence have received very little attention [24].