An integrated survey in Optical Networks: Concepts, Components and Problems

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Summary
In optical networks, a connection is used to transmit data between source and destination nodes via lightpaths. The optical signal transmitted along a lightpath requires cross-connect switches (OXCs) and telecommunication carriers to switch high-speed optical signals in a fiber optic network. As a signal propagates from the source to the destination, the signal quality is continuously degraded by optical network components and impairments. Wavelength routing networks have two main problems: network design (fiber topology) and traffic requirements (traffic matrix). The network design problem is divided into lightpath topology design (LTD) and routing and wavelength assignment (RWA) problems. The RWA problem is more important for increasing the effectiveness of optical networks. The lightpath routing sub-problem requires determining the physical links for each lightpath that consist of optical channels. The wavelength assignment (WA) sub-problem requires determining the wavelength that each lightpath uses, i.e., assigning a wavelength to each lightpath in the logical topology such that wavelength restrictions are obeyed for each physical link. In this article, we discuss the important concepts of optical networks and the factors that affect in RWAs directly or indirectly.
Key words: Optical Network; WDM; RWA; Routing; Lightpath; Impairment Factors; OXC.

1. Introduction

Network providers are moving toward using optical networks to provide increased bandwidth and improve fiber performance. Optical systems have evolved significantly [13]. Starting from the unrepeated point-to-point transmission in the 1980s, the inventions of wavelength division multiplexing (WDM) and optical amplifiers have led to an explosion in system capacity, system reach, and network architecture. The addition of an optical layer in transport networks has provided higher capacity and has reduced costs for new applications, such as the Internet, video and multimedia interaction, and advanced digital services. These networks have three main parts:

- Components that provide routing and grooming
- Optical technologies
- Restoration at the wavelength level as well as wavelength-based services.

Optical fiber systems have many advantages over communication systems. These advantages include the following [49]:

- ***Wider bandwidth***: The information carrying capacity of a transmission system is directly proportional to the carrier frequency of the transmitted signals. The optical carrier frequency is in the range from 10^{13} to 10^{15} Hz, whereas the radio wave frequency is about 10^6 Hz and the microwave frequency is about 10^{10} Hz. Thus, the optical fiber yields a greater transmission bandwidth than the conventional communication systems, and the data rate or number of bits per second is greater in the optical fiber communication system. Furthermore, the wavelength division multiplexing operation of the data rate and information carrying capacity of optical fibers is greater by many orders of magnitude.
- ***Low transmission loss***: With the use of ultra low loss fibers and erbium doped silica fibers as optical amplifiers, one can achieve almost lossless transmission. In modern optical fiber telecommunication systems, fibers with a transmission loss of 0.002 dB/km are used. Furthermore, using erbium-doped silica fibers over a short length in the transmission path at selective points allows the appropriate optical amplification to be achieved. Thus, the repeater spacing is greater than 100 km. Because amplification occurs in the optical domain itself, the distortion produced during the strengthening of the signal is almost negligible.
- ***Dielectric waveguide***: Optical fibers are made from silica, which is an electrical insulator. Therefore, they do not pickup any electromagnetic waves or high current lightning. Optical fibers are also suitable in explosive environments. Furthermore, the optical fibers are not affected by any interference originating from power cables, railway power lines and radio waves. No cross talk exists between the fibers, even though there are so many fibers in a cable because of the absence of optical interference between the fibers.
- ***Signal security***: The signal transmitted through the fibers does not radiate. Furthermore, the signal cannot be tapped easily from a fiber. Therefore, optical fiber communication provides one hundred percent signal security.

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- ***Small size and weight:*** Fiber optic cables are developed with small radii, and they are flexible, compact and lightweight. The fiber cables can be bent or twisted without damage. Furthermore, the optical fiber cables are superior to copper cables in terms of storage, ability to be handled, installation and transportation, maintaining comparable strength and durability.

2. MATERIALS AND METHODS

2.1 Optical Network Properties

Optical technologies have three properties for next-generation access networks [6]:

point-to-point topologies, passive optical networks, and free-space optics.

- Point-to-point topologies: Point-to-point dedicated fiber links can connect each subscriber to the telecom central office (CO), as illustrated in Figure 1.a. This architecture is simple but expensive due to the extensive amount of fiber required and is known as an **opaque** network. An alternative approach is to use an active star topology, where a curb switch is placed close to the subscribers to multiplex/de-multiplex signals between the subscribers and the CO. This alternative in Figure 1.b is more cost effective in terms of the amount of fiber used. A disadvantage of this approach is that the curb switch is an active component that requires electrical power as well as backup power at the curb-unit location.

- Passive optical networks: Passive optical networks (PONs) replace the curb switch with a passive optical component, such as an optical splitter (Figure 1.c). This topology is important because it is suitable and useable for PONs, including the tree-and-branch, ring, and bus networks. Using a PON decreases the total amount of fiber deployed, the total number of optical transceivers in the system, and electrical power consumption. Presently, two PON technologies are being investigated: Automated Teller Machine (ATM) PON (APON) and Ethernet PON (EPON). APON uses ATM as their layer-2 protocol; thus, they can provide quality-of-service features. EPOM encapsulates all data in Ethernet frames and can provide a relatively cheap solution compared to APONs. Additionally, EPON is becoming the favorite and is being standardized as a solution for access networks in the IEEE 802.3ah group. In Kramer and Pesavento (2000), design issues are discussed and a new protocol (IPACT) for EPON is proposed.
- Optical wireless technology (free space optics): Low-power infrared lasers can be used to transmit high-speed data via point-to-point (up to 10 Gbps) or meshed (up to 622 Mbps) topologies. An optical data connection can be established through the air via lasers sitting on rooftops aimed at a receiver. Under ideal atmospheric conditions, this technology has a transmission range of up to 4 km. Several challenges need to be addressed for optical wireless technology, including weather conditions, movement of buildings, flying objects, and safety considerations.

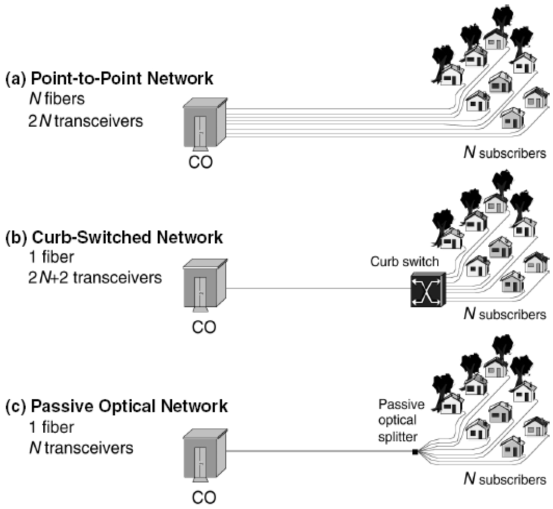

Fig. 1 Different technologies for fiber-to-the-home (FTTH).

Ultimately, nodes in optical networks electrical signals are converted to the optical domain for transmission. At intermediate nodes (e.g., switches, add-drop multiplexers, and repeaters), the signals are converted to the electrical domain for processing and are converted back to the optical domain for transmission along the next hop, the OEO (optical-electrical-optical) conversion. Multiple channels, each using a different wavelength, can be used to transmit multiple information signals at the same time in a fiber.

The goal in developing optical networks is to move toward dynamic all-optical networks, which are also called transparent networks and include circuit-switched, burst-switched, and packet-switched networks. In all-optical networks, information is conveyed from sender to recipient completely in the optical domain without OEO conversions in intermediate nodes. These networks have many advantages. The large number of devices for OEO conversion is not needed and greatly reduces costs. The decreased number of components in a network reduce the amount of required intervention and probability of network elements failing. Moreover, dynamic bandwidth provisioning can bring new gains to carrier companies. Figure 2 shows the structure of a point-to-point optical transmission system [24]. The functions of its components will be described later.

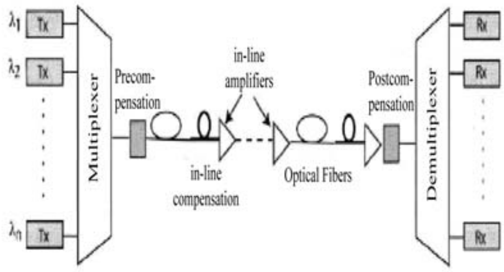

Fig. 2 Structure of a point-to-point WDM transmission system.

2.2 Optical network components

We now discuss the physical principles behind the operation of the most important components of optical communication systems. The major components used in modern optical networks are the following:

- *Transmitters*: Optical transmitters usually use a semiconductor laser diode as a light source. Its working principle is based on the physical phenomenon of stimulated emission. As an example, Figure 3 shows the structure of a DFB (distributed feed-back) laser diode [25].

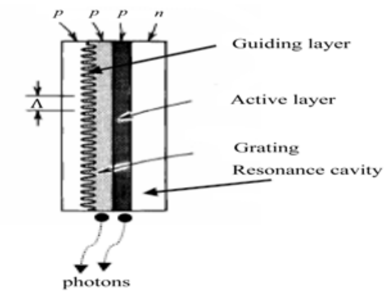

Fig. 3 Structure of a DFB laser. The periodic grating structure works as a distributed reflective mirror, thus the name DFB.

- *Multiplexers and Demultiplexers:* Multiplexers and demultiplexers are important components for wavelength-based networks. They are used to multiplex several channels onto one fiber for transmission and demultiplex signals into separate channels for routing and detection, respectively. Figure 4 shows the structure of a simple optical demultiplexer [26].

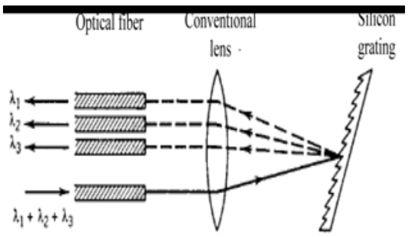

Fig. 4 Structure of an optical demultiplexer. Input wavelengths are directed to different output fibers by the diffraction grating.

There are two other types of multiplexer and demultiplexer that are shown in Figure 5 [27]. They are used to add one channel or drop one channel from an optical fiber; thus, they are called add-drop multiplexers. They are usually used in metro or local optical networks.

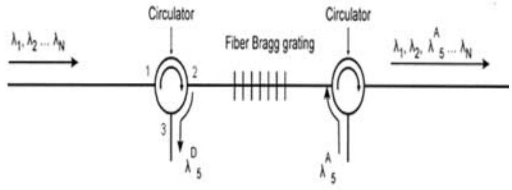

Fig. 5 Structure of an add-drop multiplexer.

In Figure 5, the input channels λ_1, λ_2, ... and λ_N go into the circulator from port 1 and out from port 2. However, wavelength λ_5 is reflected back by the fiber Bragg grating and exits the circulator via port 3; thus, this channel is dropped. Similarly, a channel can be added as shown on the right side of the figure.

- *Fiber Properties:* Single-mode fibers are widely used in today's optical communication networks. Such fibers have attenuations as low as 0.2 dB/Km in the 1550 nm wavelength range and are made of silica glass, which is much cheaper than other transmission mediums, such as copper coax cable. Figure 6 shows the cross-sectional structure of an optical fiber and the geometric optics view of wave propagation in a single-mode fiber [28].

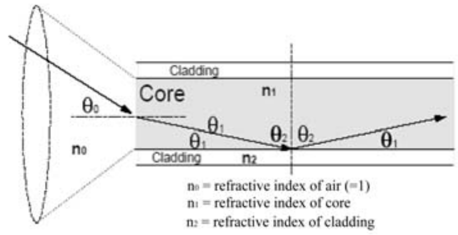

Fig. 6 Structure of a single-mode fiber and geometric optics theory of wave guides.

In Figure 6, the fiber has cylindrical geometry. It has a core with refractive index n1 and an outer cladding layer with a smaller refractive index n2. Plastic protective layers are outside of the cladding, which are not shown in the figure. The working principle that guides the light in the optical fiber is total internal refection. When the incident angle is smaller than the critical angle (_0 in Figure 2.5), light in the fiber will incur total internal refection, and the entire signal energy will be confined in the core.

- *Optical Amplifiers:* There are several different types of optical amplifiers, including semiconductor optical amplifiers (SOAs), erbium-doped fiber amplifiers (EDFAs), erbium-doped waveguide amplifiers (EDWAs), and Raman amplifiers. EDFAs are the most commonly used amplifiers in current optical networks, especially for long distance networks. EDFAs provide impressive performance, including high gain (up to 30 dB), wide bandwidth, and low noise. The structure of an EDFA is shown in Figure 7 [29].

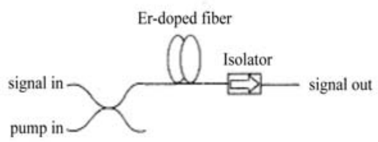

Fig. 7 Structure of an EDFA using the co-propagating pumping scheme.

As seen in Figure 7, the input signal and the pump are coupled in an Erbium-adopted fiber. In the fiber, the signal is amplified by the process of stimulated emission, while the pump is attenuated due to the energy transfer from pump photons to erbium ions. Another process, spontaneous emission, generates ASE noise. The isolator is used to prevent reflection from the output port from entering the amplifier and causing unwanted optical feedback.

- *Optical Switches:* Optical switches are important components for all-optical networks. Their basic function is to switch input signals with one wavelength to another output fiber. If no wavelength converters are deployed in the switch, then the input wavelength and the output wavelength are the same. These switches are the origin of the wavelength-continuity constraint in the RWA problem of optical routing. Through optical switches, wavelengths from different links can be connected and a lightpath can be constructed. There are different types of optical switches. Figure 8 shows the general structure of an optical switch [21].

As presented in Figure 8, all the wavelengths of an input fiber are first demultiplexed and connected to an array of wavelength routing switches (WRSs). Each WRS is responsible for switching one specific wavelength of each input fiber. A wavelength on an input fiber can be switched to any output fiber. There are different technologies to implement the WRSs, and thus, different types of optical switches exist.

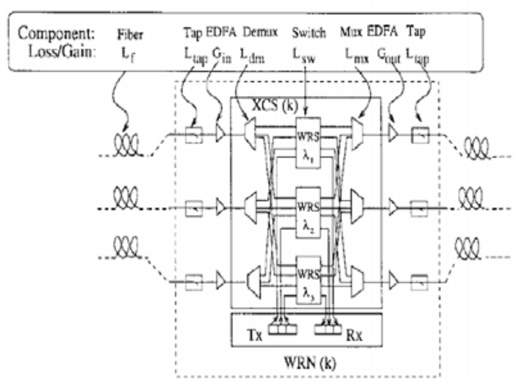

Fig. 8 The general structure of an optical switch.

- *Receivers:* Optical signals are converted to the electrical domain using a photo-detector. Figure 9 shows the structure and working principle of a simple pin detector [31].

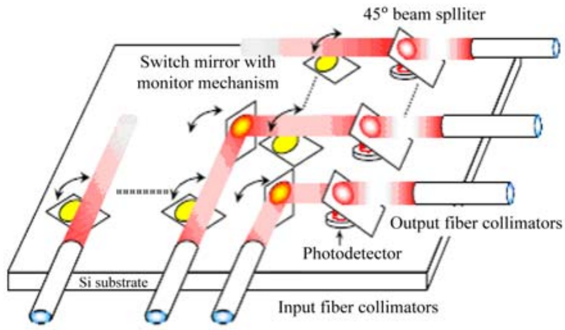

Fig. 9 Structure of a MEMS wavelength routing switch. Micro-mirrors are used to guide input beam to different outputs.

2.3 Multiplexing Techniques

There are basically two ways to increase the fiber capacity in transmissions, as shown in Figure 10 [50].

TDM (Time Division Multiplexing): TDM is a method for transmitting multiple digitized data, voice, and video signals at the same time over a single communication medium by interleaving pulses that represent bits from different channels or time slots. Many lower-speed data streams are multiplexed into a higher-speed stream at the transmission bit rate by means of electronic TDM. The multiplexer combines the lower-speed streams to achieve the higher-speed stream.

WDM (Wavelength Division Multiplexing): WDM is basically the same as frequency division multiplexing (FDM), which has been used in radio systems for more than a century. The term FDM is used widely in radio communication, but WDM is used in the context of optical communication, perhaps because FDM was studied first by communications engineers and WDM by physicists. The idea is to transmit data at the same time at multiple carrier wavelengths (or, equivalently, frequencies or colors) over a fiber. In section 4, we will explain optical WDM networks in more detail.

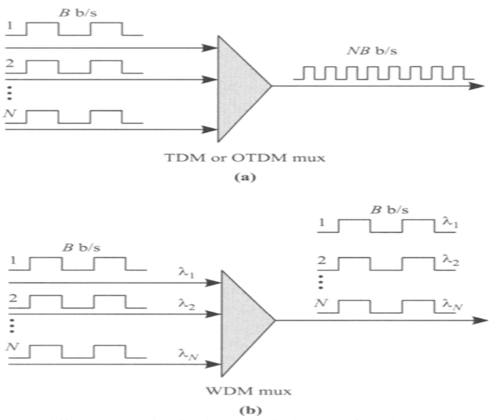

Fig. 10 Different multiplexing techniques for increasing the transmission capacity on an optical fiber. (a) Electronic or optical time division multiplexing and (b) wavelength division multiplexing. Both multiplexing techniques take in N data streams, each with B b/s, and multiplex them into a single fiber with a total aggregate rate of *NB* b/s.

WDM and TDM both are methods that increase the transmission capacity and are complementary to each other. Consequently, most networks today use a combination of TDM and WDM. The critical question today is determining what combination of TDM and WDM should be used in carriers. For example, suppose a carrier wants to install an 80 Gb/s link. Should 32 WDM channels at 2.5 Gb/s each be used or should we use 10 WDM channels at 8 Gb/s each? The answer depends on a number of factors, including the type and parameters of the fiber used in the link and the services that the carrier wishes to provide using that link. Using a combination of WDM and TDM, systems with transmission capacities of around 1 Tb/s over a single fiber are becoming commercially available, and no doubt systems with higher capacities operating over longer distances will emerge in the future.

2.4 Optical WDM Networks

An optical WDM network is a network with optical fiber transmission links that has an architecture designed with the unique features of fibers and WDM [1]. WDM networks ensure the existence of an all-optical information highway that is capable of providing a broad scope of applications that involve the transport of massive amounts of data and/or require very fast response times. Such applications include video on demand and teleconferencing, telemedicine applications, multimedia document distribution, remote supercomputer visualization, and potentially many more. Therefore, optical WDM networks have been the subject of a large quantity of theoretical and empirical research [4], [5].

In WDM networks, communication between optical cross-connect (OXC) switches occurs along optical WDM channels, which are commonly referred to as lightpaths. An OXC is a device used by telecommunication carriers to switch high-speed optical signals in a fiber optic network. The OXCs supply the switching and routing operations to support the lightpaths between end nodes. An OXC takes in an optical signal at all of the wavelengths at an input port, and can switch it to a special output port, independent of the other wavelengths. An OXC with N input and N output ports capable of handling W wavelengths per port can be thought of as W independent N*N switches. These switches have to be preceded by a wavelength demultiplexer and followed by a wavelength multiplexer to perform an OXC, as shown in Figure 11 [1]. Thus, an OXC can cross-connect the same wavelengths from the input to the output, where the connection model of each wavelength is independent of the others. Fittingly, the OXCs can be configured along the physical path;lightpath may be established between any pair of edge nodes.

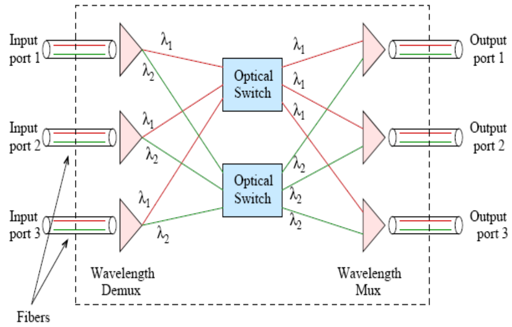

Fig. 11 A 3*3 optical cross-connect (OXC) with two wavelengths per fiber.

The architecture for wide-area WDM networks that are expected to form the basis for future all-optical infrastructures is based on the concept of wavelength routing. A wavelength routing network, shown in Figure 12, consists of two types of nodes: optical cross-connects (OXCs), which connect the fibers in the network, and edge nodes, which provide an interface between non-optical end systems (such as IP routers, ATM switches, or supercomputers) and the optical core. Access nodes provide the terminating points (sources and destinations) for the optical signal paths; the communication paths may continue outside the optical part of the network in electrical form [1].

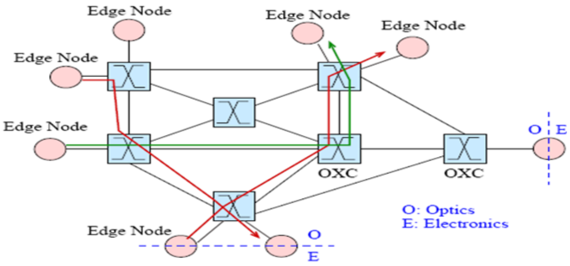

Fig. 12 A wavelength routed through a WDM network.

The services that a wavelength routed network are expected to provide suggest that ending systems must be attached to edge nodes in the form of lightpaths implemented using lightpath. Lightpaths (also referred to as λ-channels), are clear optical paths between two edge nodes and are shown in Figure 10 as green and red directed lines. Information transmitted on a lightpath is not converted to and from electrical form within the optical network; thus, the architecture of the optical network nodes can be very simple because they do not need to do any signal processing. Additionally, because a lightpath acts as a transparent channel between the sender and recipient edge node, there is nothing in the signal path to reduce the throughput of the fibers.

For an optical lightpath, the set of co-propagating lightpaths can change along its route. At a switch node, some lightpaths can diverge from their routes, and new lightpaths can co-propagate along the next optical link. Figure 13 shows an example [13].

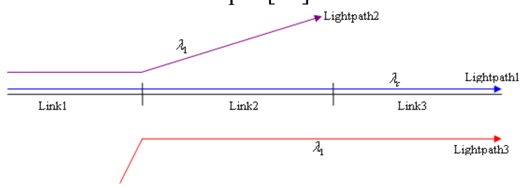

Fig. 13 Lightpath 1 and its co-propagating lightpaths. λc is the wavelength used by the probe lightpath Lightpath 1.

Optical transmission systems have developed through five generations [13]. The current generation uses low-attenuation single-mode fibers (SMFs) or dispersion shifted fibers (DSFs) as the transmission medium. A basic property of single mode optical fiber is its huge low-loss bandwidth (tens of terahertz) [1]. However, due to dispersion and restrictions in optical device technology, single channel transmission is limited to only a small fragment of the fiber capacity. To take advantage of the capabilities of the fiber, WDM technology is often used. With WDM, a number of distinct wavelengths are used to implement separate channels [2]. An optical fiber can also carry several channels in parallel, each on a particular wavelength [1]. The number of wavelengths that each fiber can carry at the same time is restricted by the physical characteristics of the fiber and the state of the optical technology used to join these wavelengths onto the fiber and separate them out of the fiber.

Unfortunately, due to the mismatch between aggregate fiber capacity and high electronic processing speeds, simply upgrading existing point-to-point fiber links to WDM creates the well-known electro-optic bottleneck [3]: rather than achieving the multi-terabit-per-second throughput of the fiber, one has to settle for the multi-gigabit-per-second throughput that can be expected of the electronic devices where the optical signals terminate. Overcoming the electro-optic bottleneck, therefore, involves designing architectures that connect the fiber links. An optical WDM network is a network with optical fiber transmission links and an architecture that is designed to exploit the unique features of fibers and WDM. Such networks offer the promise of an all-optical information highway that is capable of supporting a wide range of applications that involve the transport of massive amounts of data and/or require very fast response times. Such applications include video on demand and teleconferencing, telemedicine applications, multimedia document distribution, remote supercomputer visualization, and potentially many more. Consequently, optical WDM networks have been the subject of extensive theoretical and experimental research [4], [5].

2.5 Problems of Designing Wavelength and Routing

Wavelength-routing network design is difficult: **fiber topology** and **traffic requirements (traffic matrix)** are specified are two general problems [50].

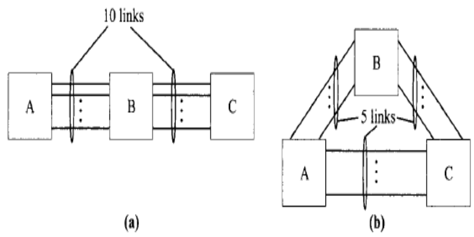

Fig. 14 (a) The lightpath topology of the three-node network corresponding to (a) that is seen by the routers. Routers A-B and B-C are connected by 10 parallel links. (b) The lightpath topology of the three-node network. All pairs of routers, A-B, B-C, and C-A, are connected by 5 parallel links.

In our example, the fiber topology is linear with three nodes, and the traffic requirement is 50 Gb/s between every pair of these nodes. The task is to design a lightpath topology that connects the IP routers and to realize this topology within the optical layer. In our example, two lightpath topologies that meet the traffic requirements are shown in Figure 14 [50].

2.6 Network design and fiber topology problems

- *Lightpath Topology Design* (LTD) *problem:* The LTD problem requires determining the logical topology that must be imposed on the physical topology, that is, determining the lightpaths in terms of their source and destination edge nodes [54].
- *Routing and Wavelength Assignment* (RWA) *problem:* The RWA problem requires determining the physical links that make up each lightpath and route the lightpaths over the physical topology. Moreover, a wavelength must be assigned to each lightpath in the logical topology such that wavelength restrictions are obeyed for each physical link [54].

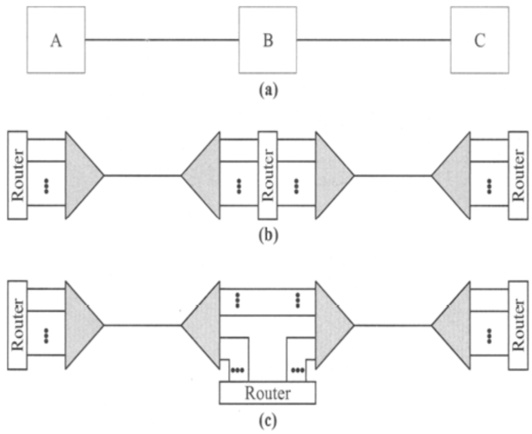

Fig. 15 (a) A three-node network. (b) Nodes A-B and B-C are interconnected by WDM links. All wavelengths are dropped and added at node B. (c) Half the wavelengths pass through optically at node B, which reduces the number of router ports at node B.

The RWA problem is simple to solve in this example because there is only one route in the fiber topology between every pair of nodes. In a general topology, the RWA problem can be quite difficult. The realization of the two lightpath topologies of Figure 14 is shown in Figures 15(b) and (c). In section 6, we focused on RWA problem in optical networks.
A unique feature of optical WDM networks is the tight coupling between routing and wavelength selection [1]. As seen in Figure 12, a lightpath is implemented by selecting a path of physical links between the source and destination edge nodes and reserving a particular wavelength on each of these links for the lightpath. Thus, establishing an optical connection requires both routing (selecting a suitable path) and wavelength assignment (allocating an available wavelength for the connection). The resulting problem is referred to as the routing and wavelength assignment (RWA) problem [7], and it is significantly more difficult than the routing problem in electronic networks. The additional complexity arises from the fact that routing and wavelength assignments are subject to the following two constraints [1]:

- Wavelength continuity constraint: a lightpath must use the same wavelength on all the links along its path from the source to the destination edge node. This constraint is illustrated in Figure 1 in which each lightpath is represented by a single color (wavelength) along all the links in its path.
- Distinct wavelength constraint: all lightpaths using the same link (fiber) must be allocated distinct wavelengths. In Figure 12, this constraint is satisfied because the two lightpaths sharing a link are shown in different colors (wavelengths).

2.7 Grooming the higher-layer traffic

The term *grooming* is usually used to refer to the packing of low-speed SONET/SDH circuits (for example, STS-1) into higher-speed circuits (for example, STS-48 or STS-192). This operation is carried out using digital cross-connects. While the term is not typically applied to IP routers, conceptually, IP routers can be considered to provide the grooming operation at the packet level. To reap the benefits of optical pass-through, the higher-layer traffic should be groomed properly. For example, in Figure 15(c), all the traffic destined for node B should be groomed onto a few wavelengths so that only those wavelengths need to be dropped at node B. Otherwise, node B will have to drop more wavelengths, which increases the network cost [50].

3. RESULTS AND DISCUSSION

3.1 RWA Problem in Optical Networks

Optical networking, like all of the other networks, has many problems. One general problem of all-optical routing is finding a path and a free wavelength for a source-destination pair such that traffic data can be transmitted along the lightpath (path + wavelength) without the need to convert to an electrical signal or change wavelength at intermediate nodes. This requirement is referred to in the literature as the RWA problem of optical routing. The general aim of the RWA problem is to increase the number of established connections. Each connection request should be given a route and wavelength. The wavelength must be consistent for the entire path, unless wavelength converters are included. Two connection requests can share the same optical link provided that they use different wavelengths.

The RWA problem in optical networks is demonstrated in Figure 16, where it is assumed that each fiber can carry two wavelengths [1]. The effect of the wavelength continuity constraint is represented by duplicating the network into as many copies as the number of wavelengths (in this case, two). If wavelength i is selected for a lightpath, the source and destination edge nodes communicate over the i-th copy of the network. Thus, finding a path for a connection may potentially involve solving W routing problems for a network with W wavelengths, one for each copy of the network.

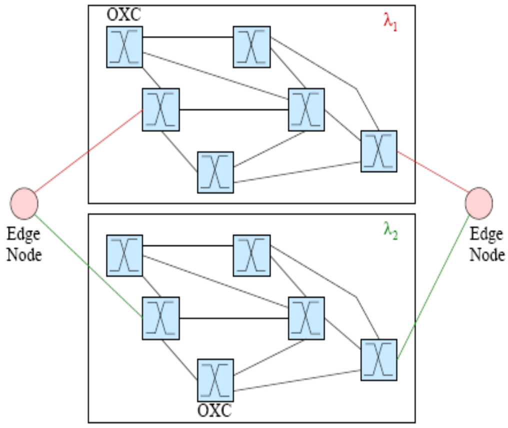

Fig. 16 The RWA problem with two wavelengths per fiber.

Traditionally, the RWA problem is addressed by a two-step process to decrease complexity [13]: first, a path from the source to the destination is found using a routing algorithm, and then a free wavelength on the chosen path is determined using a wavelength-assignment algorithm. The constraints of the RWA problem include wavelength continuity, physical impairments, and traffic engineering considerations. The wavelength-continuity constraint requires a connection to use the same wavelength along a lightpath. In some networks, wavelength converters are deployed at switch nodes, and the wavelength continuity constraint can be relaxed. However, wavelength converters are expensive and we assume no converter exists in the networks in our research. The traffic engineering constraints aim to improve resource-usage efficiency and decrease the probability that connections are blocked. The physical impairment constraints are used to guarantee signal quality to some level.

3.2 Classifying RWA based on Routing

Although merged RWA is a difficult problem, it can be simplified by decoupling the problem into two separate sub-problems: the routing sub-problem and the wavelength assignment sub-problem. In this section, we focus on various approaches to routing connection requests.

Many routing and wavelength assignment algorithms designed to efficiently use network resources and provide satisfactory service to network users have been proposed for all-optical networks. These routing algorithms can be classified in one of three categories*: static, adaptive* and *dynamic* [48].

- *Static routing algorithms:* In the static case, the entire set of connections is known in advance, and the problem is then to set up lightpaths for these connections in a global fashion while minimizing network resources, such as the number of wavelengths or the number of fibers in the network. Alternatively, one may attempt to set up as many of these connections as possible for a fixed number of wavelengths. The RWA problem for static traffic is known as the Static Lightpath Establishment (SLE) problem.

- *Adaptive routing algorithms:* In the adaptive case, connection requests arrive consecutively; a lightpath is established for each connection; and the lightpath remains in the network indefinitely.

- *Dynamic routing algorithms:* In the dynamic case, a lightpath is set up for each connection request as it arrives, and the lightpath is released after a finite period of time. The aim in the incremental and dynamic traffic cases is to set up lightpaths and assign wavelengths to reduce the number of blocked connections or that maximizes the number of connections that are established in the network at any time. This problem is referred to as the Dynamic Lightpath Establishment (DLE) problem. It includes setting up lightpaths and assigning wavelengths to them while reducing the probability of blocked connections or increasing the number of connections that can be established in the network over a period of time.

3.2.1 Static Routing Algorithms

In static routing algorithms (e.g., fixed routing [14], fixed-alternative routing [14]), one or several paths are pre-calculated for each source-destination pair. Static routing can reduce the connection provisioning time but cannot respond to dynamic traffic conditions in a network. Now we describe all static modes in detail:

- *Fixed Path Routing:* Fixed path routing is the simplest approach to finding a lightpath. The same fixed route for a given source and destination pair is always used. In general, this path is computed ahead of time using a shortest path algorithm, such as Dijkstra's Algorithm. While this approach is very simple, the performance is usually not adequate. If resources along the fixed path are in use, future connection requests will be blocked even though other paths may exist.

The SP-1 (Shortest Path, 1 Probe) algorithm is an example of a fixed path routing solution. This algorithm computes the shortest path using the number of optical routers as the cost function. A single probe is used to establish the connection using the shortest path. The running time is the cost of Dijkstra's algorithm: $O(m + n\log n)$, where m is the number of edges and n is the number of routers. The running time is a constant if a predetermined path is used.

This definition of SP-1 uses the hop count as the cost function. The SP-1 algorithm could be extended to use different cost functions, such as the number of EDFAs.

- *Fixed Alternate Routing:* Fixed alternate routing is an extension of fixed path routing. Instead of having just one fixed route for a given source and destination pair, several routes are stored. The probes can be sent in a series or in parallel. For each connection request, the source node attempts to find a connection on each of the paths. If all of the paths fail, then the connection is blocked. If multiple paths are available, only one of them is utilized.

The SP-p (Shortest Path, p Probes, $p > 1$) algorithm is an example of fixed alternate routing. This algorithm calculates the p shortest paths using the number of optical routers as the cost function. The running time using Yen's algorithm is $O(pn(m + n\log n))$ where m is the number of edges, n is the number of routers, and p is the number of paths. The running time is constant if the paths are precompiled.

If the logic of the traffic samples in the network is known in advance and any traffic variations take place over long time scales, the most effective technique for establishing optical connections (lightpaths) between edge nodes is by formulating and solving a static RWA problem [1]. For example, static RWA is appropriate to describe a set of semi-permanent connections. Because these connections are assumed to remain in place for relatively long periods of time, it is worthwhile to attempt to optimize the way in which network resources (e.g., physical links and wavelengths) are assigned.

The static RWA problem can be logically decomposed into four sub problems [1]: topology, which requires determining the logical topology needed for the physical topology, that is, determining the lightpaths in terms of their source and destination edge nodes; lightpath routing , which requires determining the physical links that comprise each lightpath, that is, routing the lightpaths over the physical topology; wavelength assignment, which requires determining the wavelength each lightpath uses, that is, assigning a wavelength to each lightpath in the logical topology so that wavelength restrictions are obeyed for each physical link; and traffic routing, which requires obtaining route packet traffic between source and destination edge nodes over the logical topology.

3.2.2Adaptive Routing Algorithms

Adaptive routing algorithms (e.g., shortest-path [14], shortest-cost-path [15], and least-congested-path [16]) commonly use the Dijkstra algorithm to calculate the path with the lowest cost from the source to the destination. The definition of the link cost function is important for such algorithms. Now we describe all adaptive modes in detail:

- *Adaptive Routing:* The major issue with both fixed path routing and fixed alternate routing is that neither algorithm takes into account the current state of the network. If the predetermined paths are not available, the connection request is blocked even though other paths may exist. Fixed path routing and fixed alternate routing are not aware of the current state of the system. For these reasons, most of the research in RWA currently focuses on adaptive algorithms. Five examples of adaptive routing are LORA, PABR, IA-BF, IA-FF, and Quality of Service (QoS). Adaptive algorithms fall into two categories: traditional and physically-aware. Traditional adaptive algorithms do not consider signal quality; however, physically-aware adaptive algorithms do.

  - *Traditional Adaptive RWA*:[5] The main idea behind the lexicographical routing algorithm (LORA) algorithm is to route connection requests away from congested areas of the network, which increases the probability that connection requests will be accepted. This routing is accomplished by setting the cost of each link to be $cost(l) = \beta^{usage(l)}$, where β is parameter that can be dynamically adjusted according to the traffic load and $usage(l)$ is the number of wavelengths in use on link l. A standard shortest path algorithm can then be used to find the path. Thus, each optical switch is required to broadcast recent usage information periodically. Note that LORA does not consider any physical impairment. When β is equal to one, the LORA algorithm is identical to the SP algorithm. Increasing the value of β increases the bias toward less used routes. The optimal value can be calculated using the well-known hill climbing algorithm. The optimal values of β were between 1.1 and 1.2 in the proposal.

  - *Physically Aware Adaptive RWA:* The physically aware backward reservation algorithm (PABR) is an extension of LORA. PABR is able to improve performance in two ways: it takes into account physical impairments and improves wavelength selection. As PABR is searching for an optical path, paths with an unacceptable signal quality due to linear impairments are pruned. In other words, PABR is LORA with an additional quality constraint.

Note that PABR can only consider linear impairments. Nonlinear impairments, on the other hand, cannot be possible estimated in a distributed environment because knowledge of global traffic is required.

PABR also considers signal quality when making the wavelength selection by removing all wavelengths with an unacceptable signal quality level from consideration. The

approach is called Quality First Fit, and it is discussed in the following section.
It should also be noted that both LORA and PABR can be implemented with either single-probing or multi-probing. The maximum number of probes *p* is denoted as LORA-*p* or PABR-*p*. With single-probing, only one path is selected by the route selection. With multi-probing, multiple paths are attempted in parallel, which increases the probability of connection success.

3.2.3 Dynamic Routing and Wavelength Assignment

In a dynamic traffic scenario, edge nodes submit to the network requests for lightpaths to be established as needed. Therefore, connection requests are initiated randomly. Depending on the state of the network at the time of a request, the available resources may or may not be sufficient to establish a lightpath between the source-destination edge node pair. The network state consists of the physical path (route) and wavelength assignment for all active lightpaths. The state evolves randomly in time as new lightpaths are admitted and existing lightpaths are released.

Thus, each time a request is made, an algorithm must be executed in real time to determine whether it is feasible to accommodate the request, and if so, to perform routing and wavelength assignment. If a request for a lightpath cannot be accepted because of a lack of resources, it is blocked. Consequently, most dynamic RWA algorithms for wavelength-routed networks consist of the following general steps:

- Compute a number of candidate physical paths for each source-destination edge node pair and arrange them in a path list.
- Order all wavelengths in a wavelength list.
- Starting with the path and wavelength at the top of the corresponding list, search for a feasible path and wavelength for the requested lightpath.

3.3. Classifying RWA based on Propagation

Two routing-and-assignment architectures have been proposed for all-optical networks: *centralized* and *distributed* [14].

- The centralized architecture is similar to the approach used in a circuit-switched telephone network, whereas the distributed approach is similar to a data packet network such as the Internet. In the centralized architecture, a controlling node monitors the network state and controls all resource allocation. Upon receiving a connection request, an edge node sends a message to the controlling node. The controlling node executes the routing algorithm and the wavelength-assignment algorithm. When a path and a free wavelength have been determined, the controlling node reserves resources on all nodes along the path. This architecture poses problems such as performance bottleneck, single point of failure, and scalability.

- In the distributed control architecture, information about the network state is broadcast periodically, and each edge node can compute the path upon receipt of a connection request. Distributed control is more scalable and robust. Upon receiving a connection request, an edge node first executes the routing algorithm to compute a path. It then starts the wavelength-reservation protocol. The wavelength-assignment algorithm can be executed by either the destination node or the source node to choose a free wavelength.

In the distributed control architecture, two wavelength reservation approaches can be applied: the forward reservation protocol and the backward reservation protocol. In the forward reservation, a `resv' (reservation) message (specifying the path and wavelength computed by an edge node) is sent from the source to the destination on the specified path. When an intermediate node receives `resv', it executes the resource reservation operation. When the destination node receives `resv', a `conf' (confirmation) message is sent upstream. In the backward reservation, a `probe' (probe) message (specifying the path computed by an edge node) is sent from the source to the destination. The message collects wavelength-state information on the relevant optical links from intermediate nodes as it propagates on the specified path. After receiving the `probe' message, the destination node picks one free wavelength using one of the wavelength-assignment algorithms and a `resv' message is sent upstream to finish the actual resource reservation [14].

3.4. Wavelength Assignment (WA) Problem

A special case of the RWA problem is that the paths are already given and we are asked to assign a wavelength while using the minimum number of wavelengths. This problem is called the wavelength assignment (WA) problem [48]. To solve the WA problem, the following two constraints apply:

1. *Distinct Channel Assignment (DCA):* Two paths must be assigned different wavelengths on any common link.
2. *Wavelength Continuity:* If no wavelength conversion is available, then a path must be assigned the same wavelength on all the links in it.

WA problems can be studied for both static (offline) and dynamic (online) cases. In the static case, all the routing requests are given at one time. For the dynamic case, the routing request comes in one by one, and there is no knowledge about future requests.

In static wavelength assignment, once a path has been chosen for each connection, the number of lightpaths traversing any physical fiber link defines the congestion on that particular link. Wavelengths must be assigned to each lightpath such that any two lightpaths that share the same physical link are assigned different wavelengths.

An offline wavelength assignment problem in star and ring networks that deploy multiple fibers between nodes and use WDM for transmission is considered. In particular, sharper per-fiber bounds on the number of required wavelengths are derived for the multifiber version of the assignment problem in star and ring networks. The wavelength assignment problem in multifiber networks, in which each link has exactly parallel fibers, is analyzed [51]. Three of the important wavelength assignment algorithms are the following [52]:

- *Random-fit*. Using random-fit, a set of wavelengths that can be used to establish the connection is determined. Next, a wavelength is randomly selected from the set according to a uniform probability distribution.
- *First-fit*. In the first-fit scheme, the wavelengths are numbered. The lowest numbered wavelength that can be used to establish a connection is used for the connection.

The idea of the first-fit scheme is to pack the usage of the wavelengths toward the lower end of the wavelengths so that high numbered wavelengths can contain longer continuous paths. Previous studies have shown [53] that this scheme performs better than the random-fit scheme. Because of its simplicity and high performance, this scheme is preferred in practice.

- *Most-used*. The most-used scheme furthers the idea of the first-fit scheme of packing the usage of wavelengths. In this scheme, all the available wavelengths that can be used to establish a connection are considered; the wavelength that has been used the most is selected for the connection. Wavelengths chosen using the most-used scheme are more compact than those using the first-fit scheme. Studies have shown that with precise global network state information, the most-used scheme performs slightly better than the first-fit scheme.

The two constraints that are followed for wavelength assignment are the following [51]:

1. Wavelength continuity constraint: A lightpath must use the same wavelength on all the links along the path from source to destination edge nodes.
2. Distinct wavelength constraint: All lightpaths using the same link must be allocated distinct wavelengths.

3.5 Physical Impairments

As optical signals traverse the optical fiber links and propagate through passive and/or active optical components, they encounter many impairments that affect the signal intensity level as well as its temporal, spectral and polarization properties. Physical layer impairments can be classified into linear and nonlinear effects. Linear impairments are independent of the signal power and affect each of the wavelengths (optical channels) individually, whereas nonlinear impairments affect not only each optical channel individually but also cause disturbances and interference [55], [56]. Figure 17 depicts the classification of physical layer impairments, including the linear and non-liner categories [57].

3.6 Linear Impairments

The important linear impairments are fiber attenuation, component insertion loss, amplifier spontaneous emission (ASE) noise, chromatic dispersion (CD) (or group velocity dispersion (GVD)), polarization mode dispersion (PMD), polarization dependent losses (PDL), crosstalk (XT) (both inter- and intra-channel), and filter concatenation (FC) [57]. Optical amplification in the form of EDFAs always degrades the optical signal to noise ratio (OSNR). The amplifier noise is quantified by the noise figure (NF) value, which is the ratio of the OSNR before amplification to the same ratio after amplification and is expressed in dB [55].

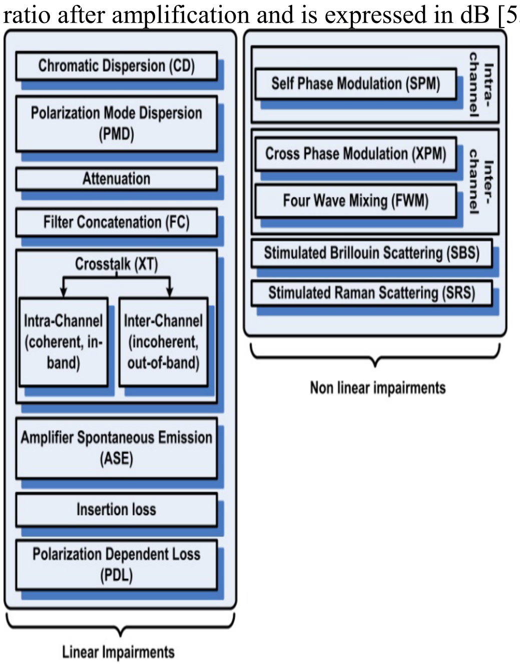

Fig. 17 Classification of physical layer impairments.

Chromatic dispersion (CD) causes pulse broadening, which affects the receiver performance by 1) reducing the pulse energy within the bit slot and 2) spreading the pulse energy beyond the allocated bit slot, which leads to inter-symbol interference (ISI). CD can be adequately (but not optimally) compensated for on a link, and/or during the design of the transmission line [55], [58], [59], [60].

PMD is not an issue for most types of fibers at 10 Gbps; however, it becomes an issue at 40 Gbps or higher rates

[56], [60], [61], [62], [63]. In general, in combination with PMD there is also polarization dependent loss (PDL), which can cause optical power variation, waveform distortion and signal-to-noise ratio fading.

Imperfect optical components (e.g., filters, demultiplexers, and switches) inevitably introduce some signal leakage either as inter-channel [55], [60] (also incoherent [60] or out-of-band [64]) or intra-channel [55], [60] (or intra-band [64]) crosstalk in WDM transmission systems.

Filter concatenation is the last physical impairment that we consider and define in this category. As an increasing number of filtering components are concatenated along the lightpath, the effective pass band of the filters becomes narrower [60]. This concatenation also makes the transmission system susceptible to filter pass band misalignment due to device imperfections, temperature variations and aging.

3.7 Non-linear Impairments

Important non-linear impairments can be summarized as self phase modulation (SPM), cross phase modulation (XPM), four-wave mixing (FWM) [22], stimulated Brillouin scattering (SBS), and stimulated Raman scattering (SRS) [65].

The nonlinear phase shift manifests as phase modulation. In SPM, the phase of the signal is modulated by its own intensity; while in XPM, the signal phase is modulated by the intensity of other signals [55]. The primary effect of these impairments is pulse broadening in the frequency domain without changing the shape of the signal.

SBS and SRS involve non-elastic scattering mechanisms [55], [65]. These impairments set an upper limit on the amount of optical power that can be launched into an optical link.

3.8 Future Works

Several routing algorithms that consider physical impairments have been proposed recently [21] [22]. Each paper considered two or three types of impairments in an example network configuration. Physical degradation effects, such as noise, linear impairments and nonlinear fiber effects, affect the signal quality along the transmission path. Depending on the channel load and transmission distance, some paths cannot, be full transparent because the transmission quality requirements cannot be fulfilled.

Estimations of the end-to-end OSNR or BER (bit error rate) have been provided. In the proposed algorithms, one lightpath that satisfies the OSNR or BER requirements is picked from a set of candidate lightpaths. The difficulty of such routing algorithms is how to make them efficient and scalable.

We would like to explore several interesting topics in both the physical layer and the network layer of all-optical networks in the future. Our studies will examine physical impairments that can adversely influence network performance. Both novel proactive and reactive approaches are proposed to improve network performance and provide QoS for users.

4. CONCLUSION

The objective of this survey was to provide an overview of the research and development work in the area of optical networking. In systems that only use WDM, each location that demultiplex signals requires an electrical network element for each channel, even if no traffic is dropping at that site. By implementing an optical network, only those wavelengths that add or drop traffic at a site need corresponding electrical nodes. Other channels can simply pass through optically, which provides tremendous cost savings in equipment and network management. In addition, space and wavelength routing of traffic avoids the high cost of electronic cross-connects, and network management is simplified.

There are three primary optical network properties: point-to-point topologies that dedicate fiber links to connect each subscriber to the telecom central office (CO), passive optical networks (PONs) that replace the curb switch with a passive optical component, such as an optical splitter, and optical wireless technology (free-space optics) that use low-power infrared lasers to transmit high-speed data via point-to-point (up to 10 Gbps) or meshed (up to 622 Mbps) topologies.

Optical transmitters usually use a semiconductor laser diode as a light source [3]. Multiplexers and demultiplexers are used to multiplex several channels onto one fiber for transmission and demultiplex signals into separate channels for routing and detection, respectively [4]. Single-mode fibers, with attenuations as low as 0.2 dB/Km in the 1550-nm wavelength range, are made of silica glass [5]. Optical amplifiers with EDFAs are the most commonly used amplifiers in current optical networks, especially for long distance networks [6]. The basic function of optical switches is to switch signals on one wavelength of an input fiber to another output fiber, and receivers convert optical signals to electrical signals.

In WDM networks, communication between optical cross-connect (OXC) switches takes place along optical WDM channels, which are commonly referred to as lightpaths. Thus, an OXC can cross-connect the different wavelengths from the input to the output, where the connection pattern of each wavelength is independent of the others.

The design of optical networks can be logically decomposed into four sub-problems: topology, which is determining the lightpaths in terms of their source and destination edge nodes; lightpath routing, which is determining the lightpath over the physical topology; wavelength allocation, which is defining a wavelength for each lightpath in the logical topology so that wavelength restrictions are obeyed for each physical link; and traffic routing, which is routing the packet traffic between the source and destination edge nodes over the logical topology. Physical layer impairments can be classified into linear (i.e., attenuation, CD, PMD, FX, crosstalk, ASE noise, insertion loss, and PDL) and nonlinear (i.e., SPM, XPM, FWM, SBS, SRS) effects. Analytical models (e.g., Q-Factor) or a hybrid approach considering analytical, simulated and experimental results are proposed for modeling the physical impairments and incorporating their impact in RWA algorithms.

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APPENDIX I

Concepts in Optical Networks

***Telecommunications Networks**:* A telecommunications network is a collection of terminals, links and nodes that are connected together to enable telecommunication between users of the terminals. Networks may use circuit switching or message switching.

Optical Networks: An optical WDM network is a network with optical fiber transmission links and an architecture that is designed to exploit the unique features of fibers and WDM [1]. Such networks offer the promise of an all-optical information highway that is capable of supporting a wide range of applications that involve the transport of massive amounts of data and/or require very fast response times. Such applications include video on demand and teleconferencing, telemedicine applications, multimedia document distribution, remote supercomputer visualization, and potentially many more. Consequently, optical WDM networks have been the subject of extensive theoretical and experimental research.

ASON (*automatically switched optical network****):*** The architecture of the next-generation dynamic all-optical networks, or the automatically switched optical network (ASON), is shown in Figure 18 [1], [23]. The network has three layers: the transport plane, the control plane, and the management plane. In the transport plane, user information is transmitted from the source to the destination in the optical domain along a lightpath. The control plane plays a crucial role and manages and allocates network resources to signal the creation of a lightpath, provide network-network interfaces (NNI) to facilitate the exchange of relevant data with neighboring domains, and provide user-network interfaces (UNI) to enable automated bandwidth provisioning on demand [23]. In Figure 1.18, the centralized management plane is shown only as an example, and distributed management planes can also be applied in optical networks.

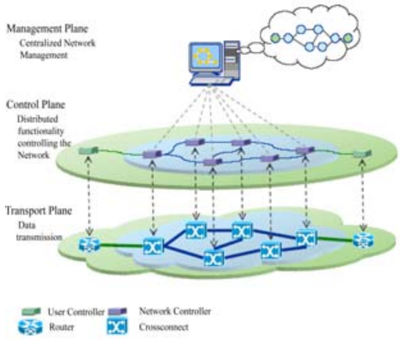
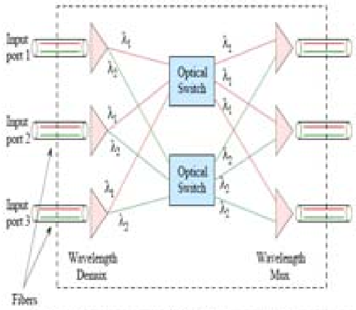


Fig. 18 Structure of an ASON network.

WDM (*wavelength division multiplexing****):*** In wavelength division multiplexing (WDM) networks, communication between optical cross-connect (OXC) switches takes place along all-optical WDM channels, which are commonly referred to as *lightpaths.* The architecture for wide-area WDM networks, which is expected to form the basis for future all-optical infrastructures, is built on the concept of wavelength routing. A wavelength routing network, consists of two types of nodes: optical cross-connects (OXCs), which connect the fibers in the network, and edge nodes, which provide the interface between non-optical end systems (such as IP routers, ATM switches, or supercomputers) and the optical core. Access nodes provide the terminating points (sources and destinations) for the optical signal paths; the communication paths may continue outside the optical part of the network in electrical form.

Wavelength Division Multiple Accesses (WDMAs): WDMAs currently have the most mature technology for accessing the bandwidth of the fiber. A broadcast network relies on the availability of a large number of wavelength channels on a fiber. Two different conversations taking place simultaneously on a broadcast network must be assigned different wavelength channels. If we want to allow all the nodes to send messages at the same time, the number of wavelength channels available to the network must be no less than the number of nodes in the network. However, due to nonlinear interactions between different wavelength channels in a fiber, the number of wavelength channels that can be supported on a fiber is limited [10]. Thus, to be able to support a large number of users on these networks, we must look at non-broadcast networks in which the same wavelength channel can be used for two or more different conversations in different parts of the network without interfering with each other. The use of a wavelength channel for two different conversations at the same time in a network is often called *wavelength reuse.* Linear lightwave networks (LLN) [11] and lightpath networks [12] are examples of the architectures that take advantage of wavelength reuse.

OXC (optical cross-connect): The OXCs provide the switching and routing functions that support the lightpaths between edge nodes. An OXC takes in an optical signal at each of the wavelengths at an input port, and can switch it to a particular output port, independent of the other wavelengths. An OXC with N input and N output ports capable of handling W wavelengths per port can be thought of as W independent NxN switches. These switches have to be preceded by a wavelength demultiplexer and followed by a wavelength multiplexer to implement an OXC, as shown in Figure 19. Thus, an OXC can cross-connect the different wavelengths from the input to the output, where the connection pattern of each wavelength is independent of the others. By appropriately configuring the OXCs along the physical path, a lightpath may be established between any pair of edge nodes.



A 3×3 optical cross-connect (OXC) with two wavelengths per fiber

Fig. 19 OXC

RWA (Routing and Wavelength Assignment): A unique feature of optical WDM networks is the tight coupling between routing and wavelength selection. A lightpath is implemented by selecting a path of physical links between the source and destination edge nodes and reserving a particular wavelength on each of these links for the lightpath. Thus, in establishing an optical connection, we must address both routing (selecting a suitable path) and wavelength assignment (allocating an available wavelength for the connection). The resulting problem is referred to as the routing and wavelength assignment (RWA) problem [7] and is significantly more difficult than the routing problem in electronic networks. The additional complexity arises from the fact that routing and wavelength assignments are subject to the following two constraints:

The wavelength continuity constraint states that a lightpath must use the same wavelength on all the links along its path from the source to destination edge node. This constraint is illustrated in Figure 19 by representing each lightpath with a single color (wavelength) along all the links in its path. The distinct wavelength constraint states that all lightpaths using the same link (fiber) must be allocated distinct wavelengths

EDFA (erbium doped fiber amplifiers): EDFAs are the most commonly used amplifiers in the current generation of optical networks, especially for long distance networks. EDFAs provide impressive performance, including high gain (up to 30 dB), wide bandwidth, and low noise.

Markov-Based Reservation protocol (MBR): The proposed Markov-Based Reservation protocol (MBR) works much like the backward reservation protocol. To decrease the probability of reservation connection, MBR uses a modified version of the first-fit algorithm to avoid selecting the free wavelengths that may be selected by other competing connection requests.

QoS: State of the art QoS routing algorithms for optical networks typically consider two or three types of physical impairments, and simplified analytical models are provided to estimate the end-to-end signal quality of a lightpath. In [21], Huang et al. considered attenuation, noise generated by EDFAs and distributed Raman amplifiers (DRAs), and optical switch crosstalk. The proposed routing algorithm [21] has a hierarchical structure: routes are determined in a network-layer module and lightpaths are verified in a physical-layer module. The route computation process is based on the shortest-path algorithm, and no information about physical layer characteristics is used to improve the algorithm efficiency. In our view, this is a shortcoming of the algorithm. Nonlinear fiber effects are also not taken into account, which is considered to be important for future optical networks.

The proposed QoS framework in [13], Lin can support both single-probing and multi-probing. In multi-probing, multiple candidate paths are probed in parallel to find one that satisfies the user QoS requirement, which results in a lower connection blocking probability but increased overhead. We also consider and provide new functions in the reservation protocol to preserve the signal quality of a lightpath, which is important for networks with dynamic traffic, where the establishing and releasing a lightpath can influence other lightpaths through inter-channel effects (e.g., XPM and FWM). Finally, numerical simulation results in different network topologies and configurations are presented and analyzed.

The proposed QoS framework has two parts: the physically aware routing algorithm (PAR) and the physically aware backward reservation protocol (PABR). The PAR algorithm takes physical impairments into account when computing a path for a connection request, which greatly improves the algorithm efficiency compared to that proposed by [21] [47].

The route computation engine of PAR returns a set of candidate paths that are very likely to satisfy the user QoS requirement. In the case of single-probing, only one path is returned. After obtaining candidate paths from the routing algorithm, an edge node starts the PABR protocol. When the **prob** message is propagated along the computed path from the source node to the destination node, each intermediate node records which wavelengths have already been used in the `probe' message and checks whether the establishment of this lightpath will cause unacceptable signal degradation to existing lightpaths. If degradation might occur, this path is discarded and the connection request is also rejected in the case of single-probing. The intermediate nodes also record co-propagating lightpaths and the physical characteristics of constituent links of the path in the `probe' message. For each received `probe' message, the destination node picks one free wavelength that satisfies the user QoS requirement with the quality first-fit algorithm and puts the lightpath in a candidate set. After waiting a short period, the destination node randomly chooses one lightpath from the candidate set and sends a `resv' message upstream. All the other candidate lightpaths are rejected with the reason `already created'.

lightpath: A lightpath is established by tuning the transmitter at the source node and the receiver at the destination node to an appropriate wavelength and by configuring the OXCs along the path. The traffic between two nodes can be carried by the lightpath established between these nodes