

All-Optical Networking

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Abstract

A survey of recent literature on all optical networking is presented. Starting from multiplexing techniques and topological features, network design and performance issues are reviewed. Particular attention is devoted to Wavelength Division Multiplexing (WDM) networks. Static and dynamic solutions of the routing and wavelength assignment (RWA) problem are considered. Issues of current research are summarized.

1. Introduction

All optical networks are very often considered to be the main candidate for constituting the backbone that will carry global data traffic whose volume has been growing at astounding rates that are not expected to slow down in the near future. For potential researchers and students of the area, this paper presents a survey of the relevant literature published in the last decade.

According to the physical technology employed, one can identify three generations of networks (Figure 1). Networks built before the emergence of optical fiber technology are the first generation networks (i.e. networks based on copper wire or radio). The second generation networks employ fibers in traditional architectures. The choice of fiber is due to its large bandwidth, low error rate, reliability, availability, and maintainability. Although some performance improvements can be achieved by employing fibers, the performance for this generation is limited by the maximum speed of electronics (a few gigabits per second) employed in switches and end-nodes. This phenomenon is called an *electronics bottleneck*. In order to satisfy the increasing bandwidth requirements of emerging applications, totally new approaches are employed to exploit vast bandwidth (approximately 30THz in the low loss region of single mode fiber in the neighborhood of 1500nm) available in fibers. Therefore, the third generation networks are designed as *all-optical* to avoid the electronics bottleneck. That is, information is conveyed in the optical domain (without facing any electro-optical conversions) through the network until it reaches its final destination. The emergence of single mode fibers, all-optical wide-band amplifiers, optical couplers, tunable lasers (transmitters)/filters (receivers), and all-optical cross-connects [1], [2] enable the realization of third generation networks.

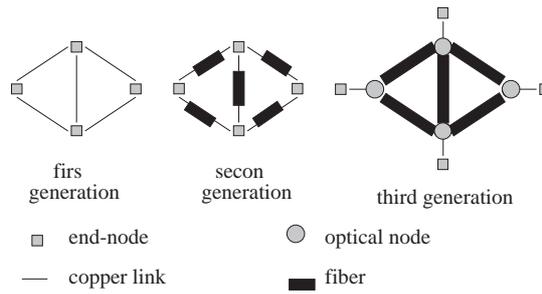


Figure 1. Three Generations of Networks

In order to make use of the vast bandwidth available without experiencing electronics bottleneck, concurrency among multiple user transmissions can be introduced. In all-optical networks, concurrency can be supplied through time slots (OTDM-optical time division multiplexing), wave shape (CDM-code division multiplexing) or wavelength (WDM-wavelength division multiplexing) [3].

In *optical time division multiplexing* (OTDM) [4], many low-speed channels, each transmitted in the form of ultra-short pulses, are time interleaved to form a single high-speed channel. By this method, the information carrying capacity of the network can be improved to 100 Gigabits/sec or higher without experiencing electronics bottleneck. In order to avoid interference between channels, transmitters should be capable of generating ultra-short pulses, which are perfectly synchronized to the the desired channel (time slot), and receivers should have a perfect synchronization to desired channel (time slot).

In *code division multiplexing* (CDM) [5], each channel is assigned a unique code sequence (very short pulse sequence), which is used to encode low-speed data. The channels are combined and transmitted in a single fiber without interfering with each other. This is possible since the code sequence of each channel is chosen such that its cross-correlation between the other channels' code sequences is small, and the spectrum of the code sequence is much larger than the signal bandwidth. Therefore, it is possible to have an aggregate network capacity beyond the speed limits of electronics. Like OTDM, CDM requires short pulse technology, and synchronization to one chip time for detection.

In WDM [6], the optical spectrum (low loss region of fibers) is carved up into a number of smaller capacity channels (Figure 2). Users can transmit and receive from these channels at peak electronic rates, and the different channels can be used simultaneously by many users. In this way, the aggregate network capacity can reach the number of channels times the rate of each channel. In order to develop an effective WDM network, each user may be able to transmit and receive from multiple channels. That is why, the tunable transmitter (laser)/tunable receivers (filter) and/or multitude of fixed transmitters/receivers are employed at end-nodes.

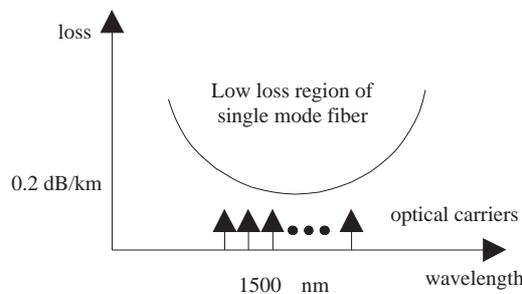


Figure 2. Wavelength Division Multiplexing

WDM is the favorite choice over OTDM, and CDM. This is due to the complex hardware requirements, and synchronization requirements of OTDM and CDM (synchronization within one time slot time and one chip time respectively). OTDM and CDM are viewed as a long-term network solution, since they rely on different and immature technology. Whereas it is possible to realize WDM systems using components that are already (or very nearly) available commercially. Moreover, WDM has an inherent property of *transparency*. Since there is no electronic processing involved in the network, channels act like independent fibers (transparent pipes) between the end nodes provided that channel bandwidths are not exceeded. Once a connection is established between the end-nodes on a WDM channel, the communicating parties have the freedom to choose the bit rate, signaling and framing conventions, etc. (even analog communication is possible). This transparency property makes it possible to support various data formats and services simultaneously on the same network. In addition to this great flexibility, transparency protects the investments against future developments. Once deployed, WDM networks will support a variety of future protocols and bit rates without making any changes to the network.

The commonly used architectural forms for WDM networks are *WDM Link*, *Passive Optical Network (PON)*, *Broadcast and Select Networks*, and *Wavelength Routing Networks*.

To increase information carrying capacity, second generation networks employ parallel fibers for individual channels. In the WDM Link approach [3], parallel fibers are replaced by wavelength channels on a single fiber (Figure 3). In long haul WDM links, all channels are amplified together by a single wide-band optical amplifier (no separate amplifier for each channel), and existing fibers are utilized efficiently by integrating more than one channel in a single fiber. Therefore, WDM link offers a very cost-effective system. The other factors that make WDM links very popular are the maturity of technology and simplicity of integration with legacy equipment. Actually, a WDM link is not a network in the usual sense, though a detailed discussion of WDM links is out of the scope of this paper.

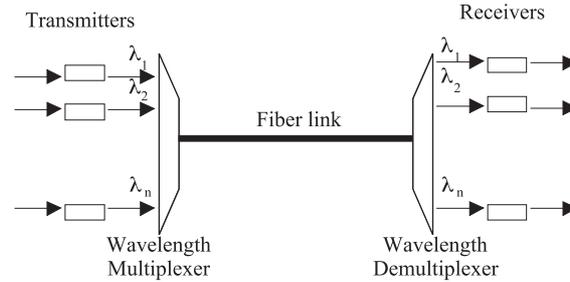


Figure 3. WDM Link

The main feature of PON [7] is to share fiber between the *Central Office* and *Optical Network Units (ONU)* (Figure 4). The PON establishes a tree structure that enables bi-directional communication between a server (central office) and multiple customers (ONUs) with centralized control and routing at central office. This architecture is a good network choice for regional communication providers. The main technological problem for the PONs is to design cheap, simple, and durable equipment for the ONUs. For detailed discussion, and experimental prototypes of PON, see [7].

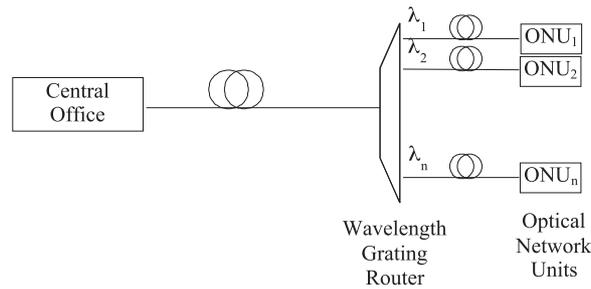


Figure 4. Passive Optical Network (PON)

Broadcast and Select Networks [8] offer an optical equivalent of radio systems. In these networks, each transmitter broadcasts its signal on a different channel, and receivers can tune to receive the desired signal. Generally, broadcast and select networks are based on a passive star coupler. This device is connected to the nodes by fibers in a star topology. It evenly distributes the signals received on the input ports to the output ports. The main networking problem for these networks is the coordination of pairs of stations in order to agree and tune their systems to transmit and receive on the same channel. The important disadvantages of these networks are splitting loss and lack of wavelength reuse. Therefore, broadcast and select networks are suitable for local area networks, though are not scalable to wide area networks. A detailed overview of broadcast and select networks is given in Section 2.

Wavelength Routing Networks [8] are composed of one or more wavelength selective nodes called *wavelength routers* and fibers interconnecting these nodes. Each wavelength router has a number of input and output ports. These ports are connected to either end-nodes or other wavelength routers. Each wavelength router makes its routing decision according to the port and wavelength of the input signal. Signals routed to the same output port should be on different wavelengths. As long as any two channels do not share the same fiber link anywhere on the network, they can use the same wavelength in wavelength routing networks. This wavelength reuse feature results in a tremendous reduction in the number of wavelengths required for building wide networks. Depending on design and components in use, a wavelength router may have a variety of capabilities. For example, its routing matrix may be static or re-configurable, and it may provide wavelength conversion or not. These features have a direct influence on the operation and scalability of the network. Therefore, wavelength routing networks are the primary choice for wide-area all-optical networks. The detailed overview of wavelength routing networks is given in Section 3.

2. Broadcast and Select Networks

Broadcast and Select Networks [8], [9] are based on the simplest all-optical organization that enables WDM. In this organization, the network infrastructure is totally made up of glass material, which acts as a propagation medium that broadcasts the individual transmissions to the whole network. The broadcast and select network model is illustrated in Figure 5. In this model, the transmitters on the end-nodes transmit the signals on distinct wavelengths to the network, and the network combines these signals and distributes the aggregate signal to the receivers. In this figure, instead of the end-nodes, only the transmitters and receivers are shown, since each end-node in a broadcast and select network has one or more transmitters or receivers.

For proper network operation, each end-node should be able to make connections with any of the other end-nodes. For this reason, each end-node should have access to multiple WDM channels. This can be accomplished by making the transmitters and/or receivers tunable over the multiple channels (wavelengths),

or having a multitude of fixed tuned transmitters and/or receivers each assigned to a different channel on an end-node. In order to avoid inter-channel interference, the transmitters should have narrow line width, and receivers can be able to filter each channel individually (i.e., narrow bandwidth filters are required). In addition, to improve efficiency, tunable components should cover all of the channels.

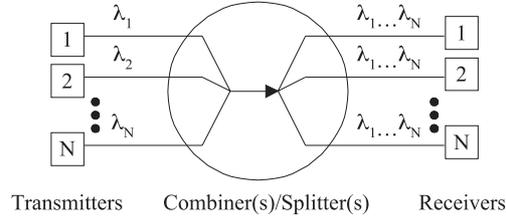


Figure 5. Broadcast and Select Network

Let us assume that there are W channels, each running at a rate of C bits/sec, available in the network. The broadcast and select organization supports at most W concurrent connections and the total capacity of this organization will be equal to $W * C$ bits/sec. It is possible to increase the channel bit rate, C , up to peak electronics rate, and in this manner it is possible to have large aggregate capacity (some orders of peak electronics rate) without forcing the limits of electronics on end-nodes. Therefore, the capacity of the network is directly proportional to the number of channels available in the network. On the other hand, the number of channels is directly related to tunability range and bandwidth of lasers and transmitters.

Inherent support for multicasting/broadcasting is an important feature of broadcast and select networks. Broadcasting and multicasting is possible in broadcast and select networks since the receivers have access to entire channels. That is, in addition to *one to one* connections, it is possible to establish *one to many* and *one to all* connections. Broadcasting and multicasting are important issues in today's networking. In the near future, many applications requiring broadcasting and/or multicasting will be widespread such as distributed computing, distributed database applications, or interactive video.

2.1. Transmitter and Receiver Arrangements

The tunability characteristics of transmitters and/or receivers determine feasible connections that can be setup between the end-nodes. Therefore, tunability is an important feature that has a direct influence on the operation of the network. According to tunability, there are four types of organizations [9], [10]: *fixed transmitter/fixed receiver*[11], *fixed transmitter/tunable receiver*[12], *tunable transmitter/fixed receiver*[6], and *tunable transmitter/tunable receiver*[13].

2.2. Physical Topologies

The main optical element used in broadcast and select infrastructures is a *coupler* [1]. Coupler is a general term for all the devices that combine light into or split light out of fiber. A *splitter* is a type of coupler to divide optical signal in one fiber to two or more fibers. On the other hand, *combiners* are the reverse of splitters. In general, splitters distribute the input optical power to output fibers. Although it is possible to manufacture a splitter with any splitting ratio, the common splitting ratio is $1/2 - 1/2$ for a two-port splitter. Therefore, an input signal suffers from a loss of about 3dB. However, in practice, couplers are not ideal devices and they introduce excess loss, caused by flaws introduced in the manufacturing process, in addition to the splitting loss.

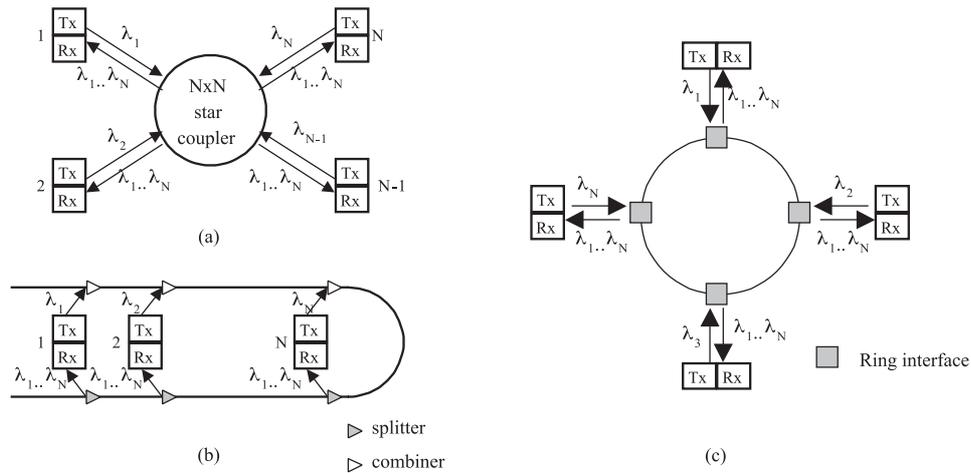


Figure 6. Broadcast and Select Organizations: a) Star b) Bus c) Ring

The most popular broadcast and select network architecture is based on a passive star coupler (Figure 6.a). This is the simplest all-optical WDM network topology. In this network, a $N \times N$ star coupler is placed on the center of the network, and each end-node is connected to the input and output ports of this star coupler by a pair of fibers. The star coupler is totally made up of glass material [1]. One way to implement a passive star coupler is to combine combiners cascaded by splitters organized in tree like structures. Another implementation of a star coupler is an integrated-optics planar star coupler where a $N \times N$ coupler is fabricated on a glass, semiconductor, or polymer substrate material. In passive star couplers, optical power at the inputs is evenly distributed on the output ports. For example, for an $N \times N$ ideal star coupler, the input signal on an input port will be distributed to all output ports with a power of $P_{out} = P_{in}/N$ on each output fiber.

Instead of a star, the physical topology can be a bus [8] or ring [7]. For example, 2×1 combiners and 1×2 splitters connected by fibers can be used to form a bus. The end-nodes transmit into the bus using combiners and receive from the bus using the splitters organized as in Figure 6.b. The star topology is preferred to the bus topology, because it is more efficient in distributing optical power. In star structure, input power is distributed evenly among all the stations. However, in a bus structure, different stations receive signals of different power levels. In addition, total excess loss grows logarithmically with the increasing number of end-nodes due to the tree-like structure of the star coupler, and grows linearly with the increasing number of end-nodes in a bus structure.

The ring topology (Figure 6.c) is also less efficient in distributing optical power compared to star topology. However, if a double ring architecture is implemented with counter directions for propagation, as in the classical FDDI configuration, it has the advantage of greater survivability. In ring architecture, each node has a unique wavelength to which its laser is tuned and an array of receivers (or a tunable receiver) which can detect all available wavelengths in the network. A splitter is used to get a small portion of signals for the receivers, and a combiner is used to inject the signal transmitted to the ring. In order to prevent interference between the new and previous signal, a filter is used before the combiner to remove the previous transmission from the stream.

Actually, selecting the suitable physical topology, as well as power considerations, should take care of optimal cable-plant design for fibers and other physical devices.

2.3. Advantages and Disadvantages

Broadcast and select networks mostly make use of passive components. The passive nature of the network presents great reliability and robustness because there is no significant reason for failures (except fiber cuts, etc.). In addition to reliability, the network is also simple and easily maintainable since the complexity of the network is at the end-nodes, and all network function should be controlled and maintained at the periphery.

The inherent nature of broadcasting and multicasting is another important advantage of broadcast and select networks. On the other hand, this broadcast nature is the cause of the main disadvantage for broadcast and select networks, *splitting loss*. Although most of the end-nodes do not use most of the channels, power from each transmitter is evenly distributed to all receivers. For example, a 1000 end-node network (i.e., 1000x1000 star coupler) introduces 30 dB splitting loss to the transmissions. Consequently, it is not possible to increase the number of end-nodes beyond certain limits, and extend the network to span long distances. It is possible to overcome these difficulties by employing wide-band (all-optical) optical amplifiers. However, in this case, the simplicity and reliability of the network is reduced due to active elements, and the overall network cost is increased.

In a broadcast and select network, the number of simultaneous connections can not exceed the number of available wavelength channels, because there is no way to make use of the occupied channels on some other part of the a network. That is, there is no *wavelength-reuse* on the network. The lack of wavelength reuse limits the achievable throughput of network. Consequently, the number of wavelength channels is the primary factor for the scalability of the network. To increase the number of wavelength channels, narrow spectral width lasers and narrow bandwidth filters, as well as tunable components with a large tunability range, should be employed. However, today's technology is limited to only hundreds of wavelength channels per fiber. Moreover, as the number of wavelengths increases, the non-linear effects of fibers (such as four-wave mixing, cross phase modulation) become a limiting factor [2]. An alternative for increasing the number of channels is to make use of a wider area in the low-loss region of the fiber, requiring wider tunability range. However, there is a trade-off between the tuning speed and tunability range of both transmitters and receivers [1]. Tuning time is an important factor for network operation and throughput. Large tuning delays cause a waste of system resources, especially in a high-speed environment and/or packet-switched communication.

The broadcast and select approach is suitable for LANs and MANs, and has a limited use on WANs due to the problems stated above. For example, it is not feasible to have a single star with more than several thousand nodes spanning thousands of kilometers. It may not be possible to have a sufficient number of wavelengths for such a network. Therefore, for widespread usage of broadcast and select networks, some method of interconnecting the networks in an all-optical way should be found. For example, a good method is employed in network prototype AON [14], [15]. In the AON prototype, a three level hierarchical architecture is formed with the broadcast and select network as LANs, and wavelength routing networks as MANs and WANs. Ten wavelengths are partitioned for use in the LAN, and the remaining ten are shared between MAN, and WAN. In this architecture, the LAN wavelengths are used for local communication, and the other wavelengths are filtered for routing through MANs and/or WANs to setup connections between different LANs.

2.4. Network Design and Performance Issues

There is a close relationship between hardware complexity (i.e., type and number of transmitters/receivers in end-nodes, number of wavelength channels, etc.) and performance (throughput, delay, etc.) of a broadcast

and select network. On the other hand, the cost of the overall network primarily depends on the complexity of hardware it is comprised of. Therefore, an analytical model is needed to estimate network performance as a function of design parameters, which define the hardware requirements, for the most cost-effective design. In this section, design and performance issues relevant to broadcast and select networks are investigated.

2.4.1. Circuit Switched Networks

If tunable transmitters, and/or receivers with large tuning delays, have to be used in a broadcast and select network, circuit switching would be the proper choice.

IBM's *Rainbow* WDM network prototype [12], [16] is a popular example for circuit switched broadcast and select networks. In *Rainbow*, each station is equipped with a single tunable Fabry-Perot filter, and a single fixed transmitter connected to a passive star coupler by two fibers. Each transmitter is tuned to a distinct wavelength (the tuned wavelength channel is also the address of the corresponding end-node), and the receivers are capable of tuning to any wavelength channel on the network. Therefore, it is possible for an end-node to make connection with any other end-node in the network, employing a simple *medium access protocol* based on *polling*.

In [17], a model for the *Rainbow* system is presented for analysis. The throughput of the system is derived in terms of various *system parameters* such as *message arrival rate*, *message length*, and *time-out duration*, and how throughput is affected by these parameters is examined. In the analysis, the following assumptions are made:

- Time is slotted with slot length equal to $1\mu s$, and all other parameters are normalized to slot length.
- There are N stations. Each station has a single buffer to store the message, and arrival to a non-empty buffer is blocked (i.e., no queuing).
- The arrival rate of messages to each station is σ , and the message lengths are geometrically distributed with the average of $1/\rho$ slots.
- The tuning delay for the receivers is assumed to be τ slots.
- The propagation delay between an end-node, and the passive star coupler is R slots.
- The time-out duration for the connection request is ϕ slots.

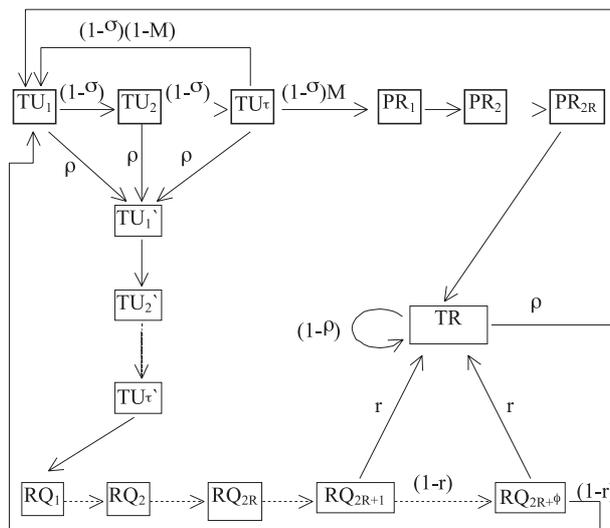


Figure 7. State Diagram for Rainbow Model

The state diagram for the model is given in Figure 7. The TU_i $i=1..τ$ are the states during which the receiver is scanning channels for connection requests (each tuning period contains $τ$ time slots for tuning period). While scanning, if a request is detected, PR_i $i=1..2R$ are the subsequent states waiting for the start of message ($2R$ is propagation delay). The end-nodes receives, or transmits, messages in state TR . If a message arrives of an end-node for transmission, scanning is stopped, and the receiver is tuned to the destination end-node's wavelength channel (for acknowledgment) in TU_i $i=1..τ$ states. Then, in RQ_i $i=1..2R+ϕ$ ($2R$ is propagation, and $ϕ$ is time-out duration) states, the end-node waits for a confirmation of the request.

It is difficult to analyze this system using Markov analysis because of the very large state space. Therefore, the Equilibrium Point Analysis (EPA) which is a means of analyzing complex systems, is used in the analysis [17]. In the EPA technique, the system is assumed to be at an equilibrium point, where the number of stations in any state remain constant all the time. The flow equations for each state in terms of the number of stations on each state are written to derive an analytical model. In this model, N_s is used to describe the number of stations in state s . Then we can use the flow equations to solve N_{TU1} , M (the probability of having a request), and r (the probability of having an acknowledgment). Then one can define normalized throughput as the average number of stations in transmit state:

$$S = \frac{N_{TR}}{N}$$

The average message delay can be defined as the period from the time of the arrival of message to the time it is transmitted:

$$D = \tau + 2R + \sum_{k=1}^{\phi} k(1-r)^{k-1} \cdot r + \frac{1}{\rho}$$

Time-out probability is defined as:

$$p_{TO} = (1-r)^{\phi}$$

Finally, blocking probability is equal to the probability that the station is not in scanning mode:

$$p_{BL} = 1 - \frac{\sum_{i=1}^{\tau} N_{TU_i}}{N}$$

Analyses [17] show that as the arrival rate increases, the throughput starts to increase, and, after some critical value, it decreases. The timeout value is an effective parameter for this critical value. Therefore, it is possible to find an optimum timeout value at which the network achieves the maximum throughput for a given arrival rate. As expected, throughput increases with message size, and normalized throughput approaches unity for large messages. On the other hand, as timeout duration increases, the timeout probability decreases. For small timeout duration, requests are timing out too quickly, resulting in high-timeout probability. For long timeout values, more connection requests will be confirmed, and throughput will increase. However, as the timeout value increases beyond a certain value, the throughput decreases while delay continues to increase. Analytical results show that the arrival rate does not have a significant effect on average delay. However, average delay increases with message size. These analytical results have been verified by simulations as well.

2.4.2. Packet Switched Networks

Packet switching in a broadcast and select network requires a significant amount of dynamic coordination between the end-nodes. In order to enable packet switching, one of the transmitters of the source and one of the receivers of the destination end-nodes should be tuned to the same wavelength channel during packet transmission. In addition, wavelength agile transmitters and/or receivers should be used, or extra mechanisms are required for the effective use of networks resources. Therefore, the most important part of the design of packet switched broadcast and select network is to develop a good protocol to coordinate packet transmissions.

The main task of these protocols is to coordinate packet transmissions to inform destinations to tune to the proper wavelength channel and avoid or handle collisions. There are several medium access protocols for packet switched single hop networks [8], [9]. These protocols are mainly based on three important approaches. The coordination of transmissions through a shared control channel is one of these approaches. In this model, one of the wavelength channels is used as a *control channel*, and end-nodes broadcast the information about their packet transmissions on this channel. Therefore, these protocols are called *pre-transmission coordination based protocols*. There are also some protocols that do not need pre-transmission coordination, such as *random access protocols*, and *protocols using transmission schedules*. In random access protocols, tunable transmitter fixed receiver organization is used because this organization does not need to inform the destination before packet transmission. On the other hand, protocols using transmission schedules assign the channels to the end-nodes in a time division multiplexed (slot time equal to packet length) way. In this method, each channel is assigned to one or more source destination pairs in each time slot to avoid both receiver and transmitter collisions.

The important performance measures for packet switched broadcast and select networks are throughput, and average packet delay. Some of the design parameters that are effective on throughput and delay are:

- Medium access protocol,
- Number of end-nodes in the network,
- Number of available wavelength channels,
- Number and type (i.e., tunable, or fixed) of transmitters and receivers in the nodes,
- Tuning delay and tunability range of tunable transmitters and receivers,
- Size of the packet queues in the end-nodes,
- Propagation and transmission delays,
- Packet length.

2.4.2.1. Pre-transmission Coordination Based Networks

In pre-transmission coordination based protocols, one of the wavelength channels is chosen as the control channel through which end-nodes broadcast the information about their packet transmissions. Packet transmission takes place on the remaining channels. Each end-node may have a separate transmitter or receiver (which can be fixed) tuned to the control channel or may use transmitter and/or receiver used for data transmissions. However, each end-node should have access to the control channel in any case. A number of protocols based on pre-transmission coordination and their performance measures are summarized in [9].

In a pre-transmission coordination based network, any end-node which wants to transmit packets should select a data channel, and transmit channel reservation information in a control packet (which includes destination address, chosen channel, packet length etc.) on the control channel. Then the data packet can be transmitted on the selected data channel. It is possible to use *ALOHA*, *slotted ALOHA*, or *carrier sense multiple access* (CSMA) medium access protocols on the control channel. ALOHA, CSMA, and N-server protocols are the possible choices for data channel protocols.

In ALOHA/ALOHA protocols, an end-node transmits its control packet at a randomly selected time and transmits the data packet on the selected data channel immediately after the control packet transmission. In slotted the ALOHA/ALOHA protocol, the control channel is accessed through the slotted ALOHA protocol, except the operation is similar to ALOHA/ALOHA protocol. In carrier sense based channel access, the carrier sensing operation is based on near-immediate feedback (considering propagation delays). However, this may not be a practical feature in a high-speed network.

In these protocols, the main problem is collision. There can be both receiver or transmitter collisions in the system according to transmitter and receiver organizations. To avoid such collisions, more complicated protocols can be employed [9]. For example, in *Receiver Collision Avoidance* (RCA) protocol, tunable transmitter/tunable receiver organization is used, and receiver collisions are avoided by adding some intelligence to the receivers. On the other hand, in *Dynamic Time-Wavelength Division Multiple Access* (DTWDM), an extra transmitter and receiver tuned to the control channel is employed to improve the performance of the system. In this network, control channel access is guaranteed to be collision free, and the packet transmission is made through a priority-based mechanism.

There are two performance bottlenecks for pre-transmission coordination based networks: the control channel, and the data channel. If the number of data channels is small, it is too hard to find an idle data channel under heavy traffic conditions, and the data channel limits the performance. If the number of data channels is large, there will be a large number of reservation packets, and the control channel will be the bottleneck.

2.4.2.2. Networks Using Random Access Protocols

Several MAC protocols, which do not need a control channel for pre-transmission coordination and enable on demand based channel access, have been proposed for broadcast and select networks, assuming the availability of rapidly tunable transmitters and receivers.

In [18], two of such protocols, namely, multichannel slotted ALOHA and random TDMA (Time Division Multiple Access), running on a star coupler based network, were investigated. In these networks, each node has a single tunable transmitter with limited tunability range, and multiple fixed receivers. In the multichannel slotted ALOHA protocol, an additional tunable receiver for receiving feedback from its transmission (to detect collisions) is used.

2.4.2.3. Networks Using Transmission Schedules

Transmission schedule based protocols are based on the application of the time division multiplexing principle in a multi-channel environment. In such a protocol, each channel is divided into equal length (i.e., packet size) time slots, and each slot is assigned to an end-node pair. Therefore, every receiver knows when to tune to a wavelength channel, and transmitters know when to transmit to a specific destination. A simple transmission schedule example is shown in Table 1a. As can be seen from the table, there is no chance for collisions in this assignment. For burst traffic demands this allocation may cause large delays. Therefore,

alternative schedules can be designed where channel allocations are less restrictive than the previous one. For example in Table 1b, each slot is assigned to more than one pair. These schedules are called *partially fixed schedules* because the number of slots used by each pair may change over time. In these schedules, channels are shared between the end-nodes, and there is a probability of transmission collisions. However, this schedule performs better than the previous one in some cases.

If the traffic demands of all the nodes are known, it is possible to develop a packet transmission schedule to minimize the average time required to transmit this demand. The demand matrix, which specifies the traffic demand of the node pairs, can be constant, or changing over time. For constant demand matrix, the designed schedule may repeat itself over time. For changing traffic conditions, traffic demand matrix can be re-constructed in time by using a control channel (over which nodes may exchange local queue information) and each node can generate the same schedule locally (independent of other nodes).

Table 1. Simple transmission schedules a) fixed b) partially fixed

Channel	$T = 0$	$T = 1$	$T = 2$
1	1 → 2	1 → 3	1 → 4
2	2 → 3	2 → 4	2 → 1
3	3 → 4	3 → 1	3 → 2
4	4 → 1	4 → 2	4 → 3

(a)

Channel	$T = 0$	$T = 1$	$T = 2$
1	1 → 2	1 → 3	1 → 4
2	2 → 3	2 → 4	2 → 1
3	3 → 4	3 → 1	3 → 2
4	4 → 1	4 → 2	4 → 3

(b)

There are several approaches for generating schedules. For example, it is possible to employ heuristics to generate an optimal multichannel TDM schedule to accommodate the traffic demand matrix. By this method, it is also possible to accommodate multicast and broadcast traffic (by employing multicast and broadcast slots) efficiently. In [19], methods for creating optimal schedules for unicast, multicast and broadcast traffic for fixed tuned transmitter, tunable receiver broadcast and select networks are investigated.

In [20], the scheduling of random traffic with tunable transmitters and fixed tuned receivers is considered, and the effects of tuning delay on the performance under uniform traffic conditions are studied. In the analyzed network, there are N nodes and W ($\leq N$) channels. Therefore, $K = N/W$ (for simplicity, K is assumed to be an integer) receivers share the same wavelength. The normalized tuning delay δ is defined as the time for a transmitter to tune, expressed in units of packet duration. The random traffic demand matrix $D = [d_{ij}]_{N \times N}$ specifies the packets to be scheduled. If $d_{ij} = 1$, the source destination pair (i,j) has a packet to be scheduled (and $d_{ij} = 0$ otherwise). The random variables $\{d_{ij}\}$ are assumed to be independent and identically distributed (i.i.d.) with $P(d_{ij} = 1) = p$. Thus D is composed of N^2 i.i.d. entries with Bernoulli distribution.

In [21] and [22], the scheduling of the packet transmissions under non-uniform traffic conditions is considered. Both systems are based on a passive star coupler, and employ one tunable transmitter and one fixed tuned receiver in the nodes.

In [21], a two pass tuning assignment algorithm (TAA) is used to schedule each node's transmitter. In the first pass, contiguous slots are assigned to nodes (by considering the constraints) starting from the node

that requires the largest number of slots on the channels. The second pass attempts to fill in the unused slots in the schedule generated in the first pass (to overlap tuning periods). This algorithm minimizes the bandwidth loss due to tuning latency. Analyses and simulations show that as N increases with respect to W (i.e., bandwidth limited region) maximum system throughput increases as well with this algorithm. To avoid performance degradation, in [22], two classes of algorithms are employed for each operating region of the network to get near-optimal length schedules.

2.5. Multi-Hop Broadcast and Select Networks

To support packet switching in a broadcast and select network, the proper assignment of wavelength channels to end-nodes is required. There are two major approaches for the channel assignment process: *per-packet basis*, and *static assignment*. In per-packet basis assignment, the wavelength channels, which are assigned to end-nodes, change for each packet destined to different end-nodes resulting in *single-hop* communication. Therefore, we need a medium access protocol to coordinate the packet transmissions, and inform destinations (Section 2.4.2). This approach requires wavelength agile tunable transmitters and/or tunable receivers and wide tuning range. However, such components are very expensive or not available commercially. Therefore, an alternative mechanism based on a fixed channel assignment, which avoids wavelength switching altogether, is proposed. This approach makes use of fixed transmitters and receivers to form a multi-hop communication environment with static channel assignment called *multi-hop networks* [8], [11], [23].

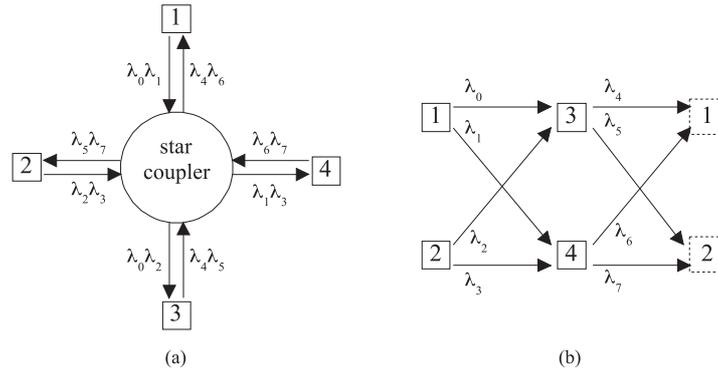


Figure 8. A Multi-Hop Network: (a) Physical Structure (b) Logical Structure

In a multi-hop network, a virtual topology is embedded on top of the physical topology that determines the actual connectivity between end-nodes. This logical topology can be embedded on a broadcast and select network by properly tuning the transmitters and receivers on the end-nodes. For example, in Figure 8 a multi-hop broadcast and select network is shown. In this network, a virtual topology (Figure 8.b) is embedded on a passive star coupler based broadcast and select architecture (Figure 8.a). In a multi-hop network, end-nodes can only transmit packets directly to the end-nodes, which are connected in the virtual topology. For this reason, the packets intended for the remaining end-nodes are routed by intermediate end-nodes until they reach to their destinations. For example, end-node 1 can not transmit a packet directly to end-node 2 in Figure 8. The packet can be sent to one of the intermediate end-nodes 2 or 3. Then the packet is forwarded to end-node 2, its destination.

The static nature of multi-hop networks presents several advantages over single hop networks. First, multi-hop networks perform better than single hop networks in packet switched environments because there is no tuning requirements per packet basis that cause large delays. In addition, multi-hop networks can

be constructed using cheap and available components without forcing technological limitations such as fast tuning and wide tuning range requirements. However, the overall cost of the network may increase if the nodal degree (i.e., number of transmitters and receivers connected to a node) of the network is high. In addition, the number of wavelength channels required in the network may increase with the overall number of nodes, and the degree of each node, resulting in increased complexity. Furthermore, the waste of a significant amount of network capacity due to forwarded traffic is the most important disadvantage of multi-hop networks. That is, network throughput is reduced by a factor, the average number of hops between the end-nodes.

The multi-hop approach is investigated in some experimental prototypes such as Teranet (in Colombia University) and STARNET [24], [25]. STARNET has an interesting feature in that it supports both single hop and multi-hop communication simultaneously on the same physical topology. In STARNET, each end-node has one fixed transmitter, one fixed receiver, and one tunable receiver. The fixed transmitter and tunable receiver are used for circuit switching between the end-nodes (single hop communication). In addition, the wavelength channels at which the fixed transmitters and fixed receivers are tuned, are organized such that they form a ring on end-nodes, and this structure is used for multi-hop packet switching. The single transmitter is shared between the circuit and packet switched networks (in time division multiplexed or sub-carrier multiplexed [3] way) for this purpose.

2.5.1. Design Requirements

In a multi-hop network, network resources must be used efficiently to achieve high performance. For this reason, some important requirements should be met in the design [26].

The most important requirement is the small average number of hops between the end-nodes. Due to multi-hopping, most of the link capacity is used for the forwarding of packets, rather than direct traffic. Therefore, the throughput is inversely proportional to the average inter-nodal distance. In addition, as the inter-nodal distance increases, the average packet delay will also increase. Therefore, the average hop distance should be as small as possible for better performance.

In a multi-hop network, the packets arrive at the nodes at a very high speed, and need to be forwarded to one of the outgoing links. Therefore, an electro-optical conversion, buffering, and routing decision is made in an intermediate end-node. To save the processing power of the end-nodes, routing procedure should be as simple as possible. In addition, a complex routing mechanism may require frequent updates of the routing tables, which may cause the waste of the capacity of communication channels.

There should be many alternative paths between the end-nodes in the logical topology. Therefore, if an end-node or link fails, the connectivity of the network will not be lost and the network can continue to convey packets via an alternative route. In general, the network is more fault-tolerant if there are more alternate paths.

Scalability is another important topic in multi-hop network design. It should be easy to add and remove any number of end-nodes from the network at any time. In this case, the reconfiguration requirements (re-tuning of the transmitters and/or receivers) should be as small as possible and the reconfiguration should cause little impact on the performance of the network.

In order to have a reduced cost system, the network should employ a small number of transmitters and receivers on end-nodes. Therefore, the nodal degree of the logical structure should be kept small. In addition, the number of wavelength channels required by the network should be kept small to ease implementation.

The other important issue is the support for non-uniform traffic patterns without performance degra-

dation (without causing large packet delays, buffer overflows in end-nodes, etc). The end-nodes can be placed in an optimal position on the virtual structure for better performance [11].

2.5.2. Logical Topologies

The logical topology employed in a multi-hop network can be either *irregular* or *regular*. It is possible to optimize the logical topology for performance criteria such as maximum throughput or minimum delay, resulting in irregular topology. However, irregular topologies suffer from routing complexity. In regular topologies, the routing is much simpler. However, due to its structured connectivity pattern, adding or removing one or more end-nodes from the network is a problem. In addition, irregular topologies can perform better in non-uniform traffic patterns, because it is possible to design a logical topology to support non-uniform traffic demands.

2.5.2.1. Irregular Topologies

Irregular topologies can be constructed to optimize some performance metrics. There are two types of objective functions for the optimization problem: *minimization of maximum flow*, and *minimization of network-wide average packet delay* [11].

A logical topology that minimizes the maximum flow on all links enables the traffic demand matrix of the network scaled up by a large factor. Therefore, for the same network, among all the logical topologies the one that has the minimum of the maximum link flows, will have a large throughput (i.e., carry much more traffic than the others can). Formally, this optimization problem can be set up as a mixed integer linear program with a set of linear constraints. Since the size of the problem grows rapidly with the increasing number of end-nodes, the exact solution of the optimization problem may be computationally demanding.

An alternative objective function in designing a logical topology is the minimization of network-wide average packet delay. The packet delay has two components: propagation delay and queuing delay. In a high-speed network, propagation delay is much more effective than queuing delays under light load conditions. In optical networks, propagation delays may have large values and depend on the physical distance between the end-nodes. Therefore, knowledge of physical locations of the end-nodes is also required for the optimization problem.

2.5.2.2. Regular Topologies

In regular topologies, the nodal connectivity pattern is very systematic and well defined. This simplifies the routing and management functions. However, the regular structures suffer from adding and removing arbitrary number of nodes to and from the network while maintaining regular structures. In addition, if the numbers of end-nodes changed, large number of transmitters and receivers may need re-tuning to re-construct the regular structure again.

Several regular multi-hop topologies proposed in the literature, and some of their features i.e., average hop distance, routing complexity, scalability, fault tolerance etc. are evaluated [7], [11], [26]. The features of some of the regular logical topologies in the literature are summarized in Table 2, and examples of the most popular topologies (*ShuffleNet*, *De Bruijn Graph*, *Manhattan Street Network* (MSN)) are also given in Figure 9.

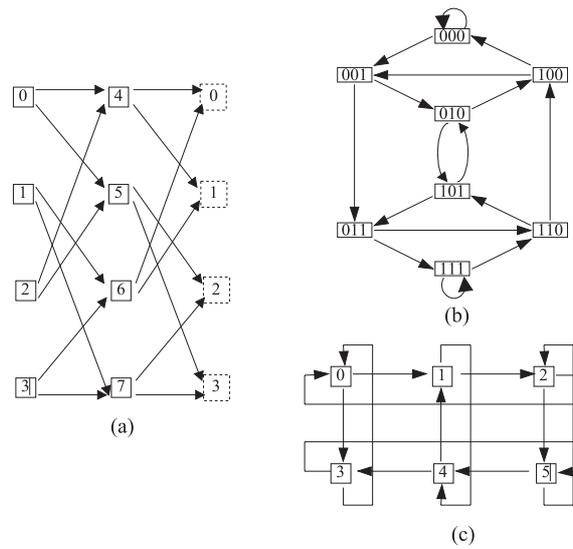


Figure 9. Multi-Hop Network Organizations: (a) Shuffle-Net, (b) De Bruijn Graph (c) Manhattan Street Network

Table 2. Regular Multi-hop Topologies [26]

Properties	ShuffleNet	De Bruijn	GEMNet	(r, k) Kautz graph	r-ary hypercube	Optimal FLBH ring	HCRNet	MSN (2DTorus)
Number of transmitters (=no. of receivers) per node (d)	r	r	≥ 2	r	$(r-1) \log_r N$	2	3	2
Number of nodes, N	kr^k	r^n	$M \times K$ (no restriction)	$r^k + r^{k-1}$	r^d	No restriction	nr_n	$N_1 \times N_2$ (no restriction)
Order of average hop distance	$\log_d N$	$\log_d N$	$\log_d N$	$\log_d N$	$\log_r N$	\sqrt{N}	$\log_d N$	\sqrt{N} (for $d = 2$)
Diameter, D	$2k_1$	$\log_d N$	$?\log_d M ? + K - 1$	k	$\log_r N$	$2(\sqrt{N}-1)$	$n + ?n/2?$	\sqrt{N}
Scalability	Poor	Poor	Fair ¹	Good	Poor	Good	Good	Good
Routing complexity	Very low	Very low	Low	Low	Very low	Low	Low	Low
Symmetry ²	Perfectly symmetric	Good ³	Good	Perfectly symmetric	Perfectly symmetric	Perfectly symmetric	Perfectly symmetric	Good ⁴
Fault Tolerance ⁵	Good	Fair	Scalable ⁶	Very Good	Good	Fair	Good	Very Good

¹ Requires $O(N)$ wavelength retuning, however, there exists a GEMNet for every N .
² Defined as standard deviation of average hop-distance from each node in the network to the other N nodes.
³ Not perfectly symmetric due to the r self-loops
⁴ Perfectly symmetric if both N_1 and N_2 are even.
⁵ Based on the number and length of the alternate paths.
⁶ For same number of nodes, GEMNets with more columns will provide more alternate paths.

Analyses show that, for the same nodal degree, De Bruijn graphs can support more end-nodes than the ShuffleNet. In addition, a simple delay analysis based on M/M/1 queues with independence assumption show that De Bruijn graphs perform better than a ShuffleNet for low to moderate loads. The comparisons on the ShuffleNet and MSN show that ShuffleNet has a smaller average hop distance. Compared to MSN, ShuffleNet has more alternate paths with a given path length from an end-node to any other end-node. It is also shown that it is possible to reach more nodes for a given path length in ShuffleNet compared to MSN. The

main advantages of a hypercube topology are its small diameter and short average hop distance compared to other topologies. However, nodal degree increases logarithmically with the number of end-nodes.

2.5.3. Wavelength Assignment

In multi-hop network design, the selection of a proper logical topology is followed by the wavelength assignment process. The wavelength assignment process is important because it determines the wavelength requirements, and the operation of the network. The simplest scheme for the wavelength assignment assigns one wavelength channel to each of the logical links. An alternative scheme, which requires a smaller number of wavelengths and transmitters, is the assignment of one wavelength channel per end-node. If the number of wavelength channels in the network is smaller than the number of end-nodes, these schemes will fail. In such a case, *shared channel* approaches can be applied in the wavelength assignment process.

If the required number of wavelengths exceeds the available number of wavelengths, it is possible to employ multiple broadcast stars in the network [13], [23]. In this case, the number of available wavelengths will be scaled up by the number of broadcast stars in the network. However, the fiber links used to connect end-nodes to the broadcast stars will be increased, resulting in large overall network costs.

2.5.3.1. One Wavelength Per Link

In the one wavelength per link scheme (Figure 8.b), every link in the logical topology is assigned to a unique wavelength channel. Therefore, each end-node pair has a distinct wavelength channel dedicated to them. The main advantage of this scheme is that it is possible to apply routing algorithms, congestion control schemes, etc. designed for traditional multi-hop networks to this system. However, this scheme requires a large number of wavelengths (number of links in the virtual topology = number of end-nodes * degree of each node), and a large number of transmitters and receivers (one for each wavelength channel).

2.5.3.2. One Wavelength Per Node

In one wavelength per node scheme [23], every end-node in the network is assigned to a distinct wavelength channel. Therefore, each node needs only a single transmitter tuned to the assigned wavelength. The wavelengths of the fixed receivers are determined by the logical topology of the network. The number of receivers in the end-nodes remains the same as the one-per link case (i.e., in-degree of each node in the logical topology).

The advantage of this scheme is that it requires fewer wavelengths, and transmitters as compared to the one per link scheme (reduced by a factor of nodal degree in the logical topology). Therefore, this scheme reduces the cost of the system. It also improves the efficiency of broadcast and multicast traffic due to a reduced number of transmissions. For homogeneous traffic, the one per node scheme has comparable capacity per unit cost with the one per link case if transmitter costs are comparable to receiver costs. However, if receiver costs are much higher than transmitter costs, in non-homogeneous traffic conditions, capacity per unit cost for the one per link scheme is always better than that of the one per node scheme.

2.5.3.3. Shared Channel Multi-hop Networks

Usually, in multi-hop networks with a large number of end-nodes, it may not be possible to have a sufficient number of wavelength channels to assign one per-link or per-node. In addition, utilization of the links will be very poor under light traffic conditions. Therefore, to improve the utilization, and/or reduce the number of wavelengths required, the wavelength channels are shared by multiple links through TDM or

any other mechanism [11], [27]. The shared channel approach may perform better due to reduced average hop distance, multicasting and broadcasting performance will be higher in such a network.

In Figure 10, a simple shared channel wavelength assignment is made in a ShuffleNet architecture. In this network, each channel is shared by two end-nodes in TDM fashion. One interesting thing about this example is that in addition to reduced number of wavelengths each node needs only one transmitter and one receiver. This example shows that it may be possible to design a multi-hop network with a reduced number of wavelengths and a reduced number of components (resulting in reduced cost).

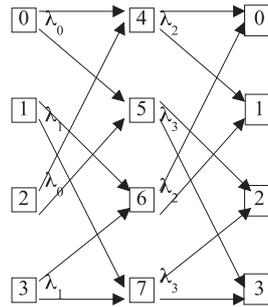


Figure 10. Shared Channel Multi-Hop Network

In [27], an analytical model to analyze the delay performance of shared channel multi-hop networks is developed. It is shown that there are limits on the number of channels (W) according to queue stability factor. When W is small, channel sharing reduces the hop distance. However, a very small W causes queue instability due to the reduced capacity of transmitters. When W is large, hop distance increases, and queuing delays increase due to forwarded traffic. Therefore, there is an optimum number of channels (which is less than the number of nodes, N) for optimum delay performance for a given traffic load. Furthermore, it is shown in [28] that, in the presence of multicast traffic, networks with $W < N$ perform better than networks where $W \geq N$, since channel sharing is employed, and the transmission of a node could be sent to more than one node (potential receiver) on each hop.

3. Wavelength Routing Networks

The splitting loss and lack of wavelength reuse restrict broadcast and select networks from spanning long distances and having large numbers of end-nodes with large throughputs. Wavelength routing networks get around these problems by channeling the transmitted power to a specific route between the source and destination end-nodes (i.e., avoiding broadcasting signals to irrelevant destinations), and reusing the wavelengths in spatially disjointed areas of the network.

Wavelength routing networks [8], [10], [29], [30] are composed of one or more wavelength selective elements and the fibers connecting them (Figure 11). These wavelength selective elements are totally made up of glass material (i.e., no electro-optical conversions) and they are called *wavelength routers*. Wavelength routers are capable of routing signals on input fibers to output fibers individually. The output port of each signal in a wavelength router is determined by the input port (fiber) it arrives through and its wavelength. The signals routed to the same output port should be on different wavelengths to avoid the mixing of different signals.

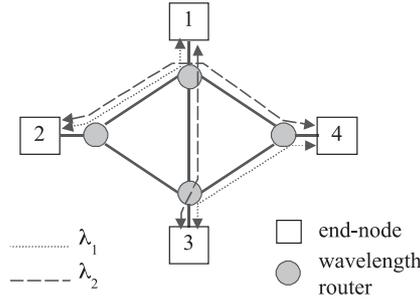


Figure 11. Wavelength Routing Network

In wavelength routing networks, each wavelength router is connected to one or more wavelength routers and/or end-nodes to constitute a physical topology. In this topology, end-to-end connections between the end-nodes are established on a wavelength channel through one or more wavelength routers. If wavelength routers are ideal, the connections between the end-nodes do not experience any splitting loss and electro-optical conversion. Therefore, such an end-to-end connection behaves like a high-speed transparent pipe between the end-nodes, which is called a *lightpath*. If two lightpaths do not share (or pass through) a fiber on their routes, they can be assigned to the same wavelength. Therefore, the spatial reuse of wavelengths can be achieved in wavelength routing networks. For example, in Figure 11, lightpaths between the end-nodes 1 – 3 and 2 – 4 (similarly 1 – 2 and 3 – 4) are assigned to the same wavelength because they do not share any fiber on their routes. Therefore, it is possible to establish large numbers of lightpaths using smaller numbers of wavelengths in a wavelength routing network.

Usually, wavelength routers are connected to each other or to end-nodes with a pair of fibers. Therefore, bi-directional lightpaths can be established between the end-nodes such that each connection follows the same route in the network and is assigned to the same wavelength in counter direction fibers. To establish a lightpath between the two end-nodes, one of the transmitters of the source and one of the destination end-node receivers should be tuned to the same wavelength. Therefore, tunable transmitters and/or receivers, or an array of fixed transmitters and receivers, should be employed in the end-nodes to have a flexible network. Moreover, the number of transmitter/receiver pairs in an end-node determines the maximum number of lightpaths that can be supported by that particular end-node simultaneously. Therefore, end-nodes should be equipped with multitude of tunable/fixed transmitter/receiver pairs to utilize network resources efficiently.

3.1. Wavelength Routers

Each wavelength router has one or more input and output ports through which it is connected to other wavelength routers and/or end-nodes by using one or more fiber links for each neighbor. Wavelength routers should be able to route signals on different wavelengths at different input ports to (possibly) different output ports independent of the signals on other input ports and on other wavelengths. According to the routing matrix present there are four major types of wavelength router architectures: *Fiber Cross-Connects*, *Add-Drop Multiplexers*, *Static Wavelength Routers*, and *Reconfigurable Wavelength Routers*.

3.1.1. Fiber Cross-Connects

Fiber cross-connect [1] is a wavelength insensitive device, which switches signals on an input port to one of the output ports as a whole. That is, the signals at different wavelengths of an input port are always routed

to the same output port. A basic cross-connect device is a 2x2 crosspoint element (Figure 12) which routes optical signals from two input ports to two output ports and has two states: bar state, and cross states. The state of cross-connect can be chosen by applying appropriate (electronic) control signals on device control ports. In bar state, the signals at the upper and lower input ports are routed to upper and lower output ports respectively. In cross state, the signals at the upper and lower input ports are routed to lower and upper output ports respectively.

The 2x2 fiber cross-connects are simple and cheap devices, and it is possible to construct larger switches (with more than two input and/or output ports) by using many of them. Actually, a fiber cross-connect is not a real wavelength router because it can not distinguish between the different wavelengths on an input port. However, in a wavelength routing network, as the number of lightpaths increase, many of the lightpaths will follow the same route through a wavelength router. By using this idea, significant cost reductions can be achieved by employing fiber cross connect and other (wavelength selective) router architectures in a single wavelength router. Therefore, lightpaths following the same route can be routed by fiber cross-connect devices, and the remaining lightpaths can be routed by other (wavelength selective) wavelength routing devices. Therefore, it is possible to organize a wavelength router as multiple layers of wavelength insensitive and wavelength sensitive devices each running at different granularity. Such a wavelength router, which is called a *Multilayer Crossconnect*, is proposed in [30].

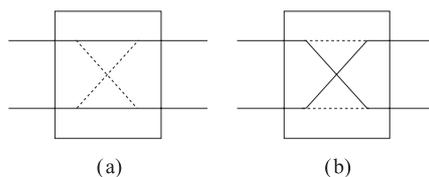


Figure 12. 2x2 Cross-Connects a) Bar State b) Cross State

3.1.2. Add-Drop Multiplexers

An add-drop multiplexer [31] is a one *input*, one *output*, one *drop* and one *add* port device. In add-drop multiplexers, one or more signals on different wavelengths at the input port are routed to the drop port. The remaining signals and the new signals (at the same wavelength of the dropped signals) at add port are combined and routed to the output port. There are several add-drop multiplexer types proposed. In fixed add-drop multiplexers, the wavelengths of added-dropped signals are fixed. Such devices can be constructed using passive elements, and have a high reliability. In reconfigurable (dynamic) add-drop multiplexers, the wavelengths of added-dropped signals can be chosen by applying proper control signals (optical or RF signals) for each wavelength to the control port. There are several all-optical architectures proposed for reconfigurable add-drop multiplexers. One such device is the *Acoustooptic Tunable Filter* (AOTF) [10] (Figure 13), which utilizes TM and TE polarization modes in a birefringent optical waveguide in LiNbO_3 . In AOTF, after passing the first polarizing beam splitter, all signals have the same polarization. For the signals at selected wavelength(s), corresponding RF drive signal(s) are injected in to a polarization converter device. Finally, selected signals are dropped by the second polarizing beam splitter device. The AOTF can be used by a passive combiner device (to add new signals) to construct a multi-wavelength configurable add-drop multiplexer.

Add-drop multiplexers are utilized in many experimental wavelength routing networks. For Example, a Scalable Multiwavelength Multi-hop Optical Network [6] model employs wavelength routers constructed

by AOTF. In [32], a reconfigurable WDM add/drop network called *MOSAIC* that may be connected in a ring or bus fashion is presented.

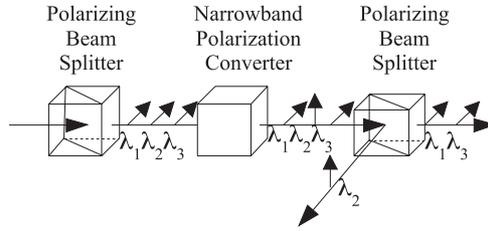


Figure 13. Acousto-optic Tunable Filter

3.1.3. Static Wavelength Routers

Wavelength routing can be accomplished by using a stage of demultiplexers (one for each input fiber) followed by a stage of multiplexers (one for each output fiber), whose inputs are hardwired to the outputs of the demultiplexers. The demultiplexers separate the signals on different wavelengths in each input fiber, and the multiplexers recombine the signals at different wavelengths coming from different input fibers. According to the wiring style (between the multiplexers and demultiplexers) the routes for the signals can be selected by a control mechanism resulting in a *reconfigurable wavelength router* (Section 3.1.4) or they may be fixed resulting in a *static wavelength router*.

It is possible to construct a static wavelength router which interconnects N input ports to N output ports in a non-interfering way using only N wavelengths (not N^2 wavelengths as expected). A 4×4 static wavelength router, which shows one possible interconnection pattern of this type, is illustrated in Figure 14. In this router, it is possible to reach from any input port to any other output port at predefined distinct wavelengths. Which wavelength on which input port gets routed to which output port depends on the routing matrix, which is determined by the internal connections, characterizing the router.

Waveguide grating router (WGR) [1] is a possible implementation of a static wavelength router shown in Figure 14. WGR is composed of two passive star couplers interconnected by a grating array, which consists of many waveguides with different lengths. Therefore, it is possible to implement a WGR as an integrated device, which can easily be fabricated at a low cost. It also provides great reliability due to its passive nature. Based on these and other advantages [33], WGR-based wavelength routers are potential choices for wavelength routing networks.

There are many wavelength routing network proposals that use static wavelength routing. For example, AON [14], [15] makes use of static routers in level-1 subnetworks. In AON, there are many level-0 subnets (broadcast and select LANs), connected to level-1 subnets through a single fiber pair. A level-1 subnet is a MAN that connects a set of level-0 subnets using static wavelength routing. The level-1 subnets are also interconnected by a single level-2 subnet (WAN) that employs reconfigurable wavelength routers.

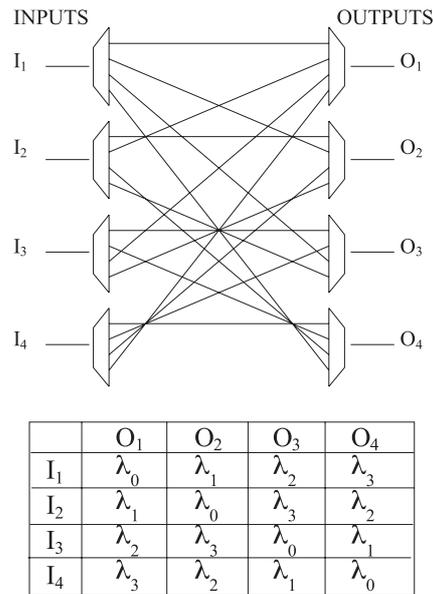


Figure 14. A 4x4 Static Wavelength Router and Its Connection Matrix

A WGR is a passive, and static wavelength router. Therefore, the connections that can be established in a WGR based network will be fixed, resulting in reduced flexibility in the network. To provide reconfiguration capabilities in the network, it is possible to introduce fiber cross-connects at the input and output ports of the WGR. By this method it is possible to build a low cost and simple wavelength routing network which is able to adapt to changing traffic demands by adjusting fiber to port interconnection patterns. Algorithms to establish lightpaths, to satisfy a given traffic demand by appropriately adjusting fiber cross-connects, are presented in [33]. The proposed architecture was shown to scale well with the number of nodes in the network

3.1.4. Reconfigurable Wavelength Routers

Reconfigurable wavelength routers [1] can route a signal on an input port at a wavelength to any output port independently from the other signals on different wavelengths on the same port. This can be accomplished by employing photonic switches between the wavelength demultiplexers and wavelength multiplexers.

A reconfigurable wavelength router consists of N demultiplexers, N multiplexers, and an array of $W \times N$ photonic switches, where W is the number of wavelengths, and N is the number of input/output ports of the wavelength router. A 3x3 reconfigurable wavelength router with two wavelengths is shown in Figure 15. All signals at the same wavelength and coming from different demultiplexers are directed to the same switch, and the switched signals are then directed to multiplexers associated to output ports. The photonic switches can be constructed by using 2x2 optical crosspoint elements (Section 3.1.1) arranged in a banyan-based fabric. Therefore, it is possible to route a signal from any input port to any output port at a given wavelength by properly setting the proper control signals on the crosspoint elements.

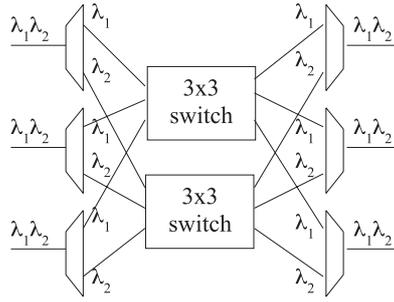


Figure 15. A 3x3 Reconfigurable Wavelength Router

Reconfigurable wavelength routers are very flexible devices because they are able to adapt to changing traffic demands by dynamically establishing or terminating lightpaths between the end-nodes in a network. In these routers, the signals routed to the same output port should be at different wavelengths. Therefore, there is a possibility of blocking if two or more signals at the same wavelength on different input ports are routed to the same output port. For this reason, while setting up lightpaths between the end-nodes, such clashes should be resolved by using a suitable routing and wavelength assignment algorithm (Section 3.7).

3.2. Wavelength Conversion

In wavelength routing networks, lightpaths should be assigned to the same wavelength along their route, and lightpaths sharing one or more fibers along their routes should be assigned to different wavelengths. This is called the *wavelength continuity constraint*. Due to this constraint, in a wavelength routing network, having at least one idle wavelength channel on all fibers along a route may not be sufficient to establish a lightpath on that route. This is because at least one idle channel on a common wavelength should exist along the route to establish a lightpath. This is illustrated in Figure 16. In this example, although there are idle channels on *Link 1* and *Link 2*, it is not possible to establish a lightpath between *Node 1* and *Node 3*, because there is no common wavelength channel available on both links.

The wavelength continuity constraint can be avoided by employing wavelength converters in the wavelength routers. Wavelength converter devices transfer a signal from a wavelength channel to a different wavelength channel. Therefore, the lightpaths can be assigned to different wavelengths along their routes. For example, in Figure 16, if there is a wavelength converter available in Node 2 a lightpath can be set up between *Node 1* and *Node 3* using wavelength channels λ_4 , λ_3 on *link 1* and *link 2* respectively.

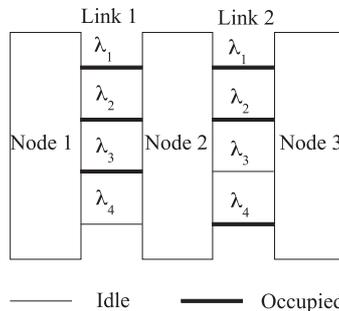


Figure 16. Blocking in Wavelength Routing Networks

Networks with wavelength converters are the equivalent traditional circuit switched networks. In circuit switched networks, a free capacity (channel) on all the links along a route between two end-nodes is

sufficient to establish a connection (circuit). Similarly, if wavelength converters are employed on wavelength routers, having an idle channel (probably at different wavelengths) along a route will be sufficient to establish a lightpath on that route. This means that using wavelength converters in wavelength routing networks may improve utilization of the fibers resulting in improved network performance.

The performance gains offered by wavelength converters are investigated in many studies. Blocking probability with and without wavelength converters increase with the number of hops H , and the amount of increase is much higher in networks without wavelength converters. Therefore, wavelength conversion gain is large in networks with large diameters. However, the interference length (i.e., expected number of links shared by two lightpaths that share some link) is also an important parameter in blocking probability. Networks with large interference lengths have smaller blocking probabilities than networks with small interference lengths, and performance improvement by using wavelength converters decreases with large L . Therefore, it is shown in [34] that effective path length (i.e., H/L) is an important factor in performance improvement achieved by wavelength converters. In [35], the performance of non-blocking centralized switch, mesh-torus network, and ring network are evaluated using analytical models and simulations. It is shown that wavelength converters can significantly improve the performance in large mesh-torus networks, while the performance gain obtained in centralized switch and ring topologies is modest. This is because effective path length in mesh topologies is much higher than that in centralized switch and ring topologies.

In addition to improved performance, wavelength converters can offer many other advantages [36] in a wavelength routing network. For example, it may be hard to find a common wavelength for longer (in hops) paths to setup a lightpath as stated previously. Therefore, wavelength converters can improve the fairness (i.e., approximately equal chance of setting up short and long lightpaths) by resolving wavelength conflicts in longer paths. In addition, if the end-nodes are equipped with fixed tuned transmitters and receivers, wavelength converters can enable the setting up of connections between end-nodes which have no transmitters and receivers tuned to a common wavelength. Wavelength converters can also improve the utilization of a wavelength if different numbers of wavelengths are available on fibers in the network. It is also possible to use wavelength converters at the interfaces of subnetworks to simplify the management of the whole network, especially if each subnetwork has different operators. This is because wavelength assignments for lightpaths can be performed in each sub-network independently from the others.

3.2.1. Wavelength Conversion Technologies

The function of a wavelength converter is to switch an optical signal from a wavelength to a different one among the available wavelengths. An ideal wavelength converter should convert any given signal on a wavelength to another wavelength. Moreover, ideal converters preserve transparency to bit rates and signal formats. Wavelength converters can be classified into two types: *optoelectronic wavelength converters*, and *all-optical wavelength converters*.

In optoelectronic wavelength conversion [37], the signal to be converted is first translated into an electrical signal using a receiver. Then, the signal is regenerated and amplified in the electrical domain. Finally, the reproduced electrical signal is used to drive a laser tuned to a desired output wavelength. That is, 3R regeneration is performed in this method. Since an electro-optical conversion is carried out, transparency is lost in optoelectronic wavelength conversion. Moreover, this method is much more complex and consumes much more power than the all-optical conversion techniques.

There are, mainly, two types of all-optical wavelength conversion [1]: Wavelength conversion using coherent effects, and wavelength conversion using cross modulation. Wavelength conversion using coherent

effects is based on wave-mixing effects, which is a non-linear an optical response of optical fiber when more than one wave is present. Wave mixing preserves the transparency, and it allows for the conversion of multiple input wavelengths to a set of multiple output wavelengths. The most commonly used wave mixing techniques are four wave mixing (FWM) and difference frequency generation (DFG), which are third-order and second-order non-linearity in fibers. Cross modulation methods make use of active optical devices such as lasers and optical amplifiers. The wavelength conversion can be achieved by optical amplifiers using cross gain modulation or cross phase modulation of an injected optical carrier at the output wavelength by the input signal. Cross modulation methods, using optical amplifiers, presently seem well suited for system use.

3.2.2. Limited Wavelength Conversion

In wavelength convertible networks, it is possible to support full wavelength conversion in all nodes resulting in a network equivalent to circuit switched networks. A possible wavelength router of this type is shown in Figure 17. In such a router, each wavelength channel on the output links is assigned to a distinct wavelength converter. Therefore, this organization is called a *dedicated wavelength convertible router*. In this router, usually, each wavelength converter is capable of converting any input wavelength to any other wavelength. The signals at different wavelengths on the input ports are first demultiplexed, and each signal is routed to one of the output ports of the non-blocking optical cross-connect linked to the desired multiplexer. If the wavelength of the signal does not match up with the corresponding port, the signal is converted to a proper wavelength by the dedicated wavelength converter.

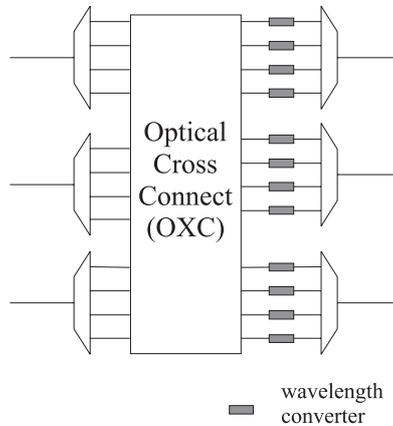


Figure 17. Dedicated Wavelength Convertible Router

In a wavelength convertible network, lightpaths may need wavelength conversion occasionally to resolve wavelength conflicts. Therefore, many of the wavelength converters in a dedicated wavelength convertible router will not be used most of the time resulting in the reduced utilization of wavelength converters. Therefore, wavelength converters can be shared in wavelength routers to have a cost-effective network. There are two approaches for sharing wavelength converters in wavelength routers [38]: *share-per-node* and *share-per-link*. Since the number of wavelength converters is not sufficient for non-blocking operation, there is a chance of blocking which is inversely proportional to the number of converters employed in these architectures.

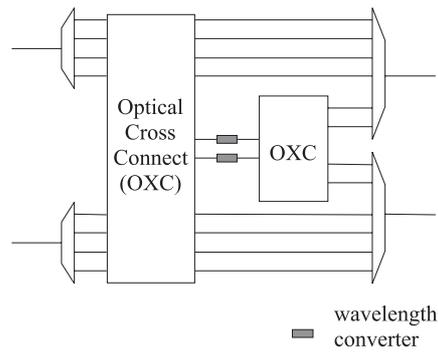


Figure 18. Share Per-Node Wavelength Convertible Router

In the share-per-node wavelength convertible router (Figure 18), each converter can be accessed by any of the signals on the input ports. In this router, the signals at proper wavelengths are directly routed to the multiplexers of the desired output port. However, if there is a wavelength conflict (i.e., two signals at the same wavelength are to be routed to the same output port), only one of the conflicting signals can be directly routed. The remaining signals can be routed through wavelength converters. These signals are first converted to an idle wavelength on the desired output link, and the desired output link is chosen by the second optical cross-connect. The main disadvantage of this method is the need for a second optical cross-connect.

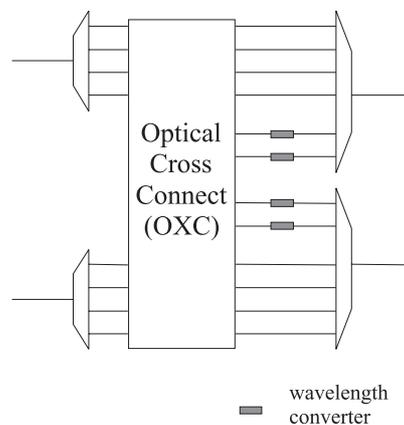


Figure 19. Share Per-Link Wavelength Convertible Router

In share-per-link wavelength convertible routers (Figure 19), each output link has its own wavelength converters, which can be accessed only by the signals that will be routed to those output ports. If there is a wavelength conflict, one of the conflicting signals is directly routed and the remaining signals are routed through wavelength converters. After conversion, they are multiplexed into the output fiber.

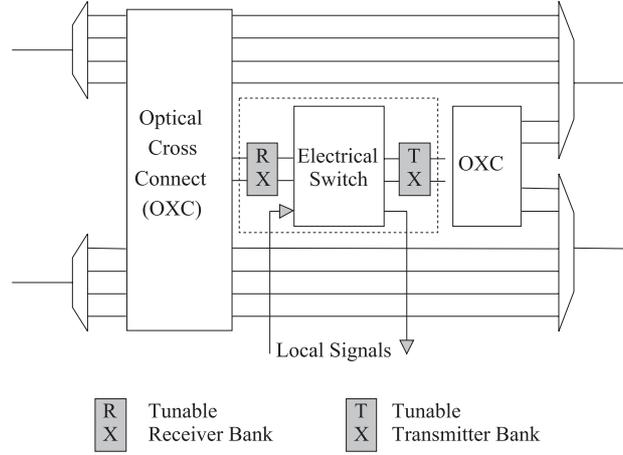


Figure 20. Share-With-Local Wavelength Convertible Router

Instead of using all-optical wavelength converters in wavelength routers, the receivers and transmitters on end-nodes, which are connected to the wavelength router, can be used for wavelength conversion. Such an organization is called a *share-with-local* wavelength convertible router. The signals, which need wavelength conversion, are routed to one of the receivers of an end-node, and this signal is routed to one of the transmitters (tuned to the desired wavelength) by an electrical switch inside that end-node. This is a more cost-effective approach than the share-per-node and share-per-link because the local transmitters and receivers also serve as wavelength converters. In terms of sharing efficiency, share-per-node approach is the best, the share-per-link approach comes next and the dedicated approach is the worst of all the choices. In terms of hardware complexity, on the other hand, the dedicated approach is the simplest, the share-per-link approach comes next and the share-per-node approach is the most complex organization.

Simulation results [38] have shown that using only a limited number of converters in each wavelength router is sufficient to provide good performance in terms of blocking probability and fairness (i.e., short and long lightpaths experience approximately the same blocking probability).

All of the limited wavelength conversion approaches presented above assume that every wavelength router in the network has a wavelength conversion capability, and that wavelength converters are ideal (i.e., any wavelength can be converted to any other wavelength). However, in some networks, *sparse wavelength conversion* is provided or *non-ideal wavelength converters* are employed.

In the sparse wavelength conversion approach, a full set of wavelength converters is employed in selected wavelength routers, and the remaining wavelength routers do not have wavelength conversion capability. It was shown that, in most cases, only a small fraction of nodes equipped with wavelength converters is sufficient for acceptable performance [30], [37]. Optimal placement of wavelength convertible routers in a network is also an important issue [36] in sparse wavelength convertible networks.

If non-ideal wavelength converters are used in wavelength routers, any wavelength can be converted to only a small subset of available wavelengths. Analytical results [39] show that the performance gain achieved by using non-ideal wavelength converters is close to the performance gain achieved by using ideal wavelength converters. It is also shown that [37] significant improvements can be achieved in the blocking probability with limited-range wavelength converters tunable over only one-quarter of the whole range.

3.3. Multi-Fiber Networks

Most of the optical networks deployed so far employ multiple fibers between end-nodes. This is due to the economic advantage of installing bundles of fibers for the purposes of fault tolerance and future network growth. Networks that employ multiple fibers between the nodes are called *multi-fiber networks* [40].

If K fibers are employed over a link between wavelength routers, and the number of wavelength channels is W , the capacity of each link will be equal to KxW channels. This is functionally equivalent to a single fiber wavelength routing network with KxW wavelength channels in each fiber. In general, in a multi-fiber network, wavelength routers serve each fiber separately. If a wavelength router has d neighbors, it uses W switches of size $dKxdK$, instead of using KxW switches of size dxd . Therefore, for the same capacity, larger switches are required in a multi-fiber network. However, such a K fiber W wavelength network is functionally equivalent to a KW wavelength network with partial wavelength conversion of degree K wavelengths. That is, multi-fibers are functionally equivalent to using limited-range wavelength converters, which can convert a signal to any of the K wavelengths among KW wavelengths. This is because a signal on a wavelength can be routed to one of the possible K fibers to reach the same destination using the same wavelength channel.

The benefits of using multiple fibers in a wavelength routing network are evaluated in [40]. It is shown that blocking performance improves dramatically with the use of only two fibers in each link. The throughput of two-fiber networks increases by an approximate factor of four with respect to single fiber networks.

In [41], an optical path accommodation design algorithm is proposed to heuristically establish lightpaths in wavelength continuous or wavelength convertible networks in which multiple fibers are employed between wavelength routers. The objective is to minimize the total number of fiber ports required at each node. Analyses show that difference between the objective functions in wavelength continuous and wavelength convertible networks decreases as the traffic intensity increases (i.e., as the number of optical fibers required to accommodate lightpaths in a link increases).

3.4. Alternative Approaches

In the wavelength routing networks reviewed so far, each lightpath is routed separately from the others and lightpaths are established as end-to-end connections between two end-nodes. However, it is possible to simplify the hardware requirements at the routing node by grouping a set of wavelength channels in a waveband. It is also possible to establish a lightpath between a node and a set of nodes using optical couplers in the wavelength routers to enable multi-cast communications.

In linear lightwave networks [42], the usable portion of the optical spectrum is divided into wavebands. Wavebands are also sub-divided into wavelength channels through which connections between end-nodes are established. The multiple wavelength channels in a waveband present a high degree of concurrency in a fiber. The routers in a linear lightwave network employ linear divider couplers and their associated control circuitry. Each router in the network performs controllable selective routing, combining, and splitting of wavebands. The combining function allows multiplexing of the signals in wavebands on two or more input fibers to a waveband in a single output fiber. The splitting function broadcasts a single waveband in an input fiber to a set of output fibers. Each station has at least one tunable transmitter and receiver. A connection is established by creating an optical signal path from the source to destination(s) by the switching action of linear divider couplers along a route. Once a route and waveband on that path is determined, a channel is selected in that waveband. Since routers can broadcast a waveband on multiple output fibers, it is possible to

establish one to many connections in linear lightwave networks. However, splitting and combining operations may cause some problems while selecting routes. For example, only the signals from mutually independent sources may be combined in a waveband on a single fiber. That is, a signal is not allowed to split and recombine with itself after propagating through some hops. Therefore, a proper routing and wavelength assignment algorithm should be employed to avoid such situations in linear lightwave networks. It was shown in [42] that it is possible to build networks of the order of one thousand nodes capable of overall throughputs up to 10s of Terabits per second.

In [43], the light-tree concept, which is a point-to-multipoint generalization of a lightpath in a wavelength routed optical network, is introduced. The proposed network architecture uses linear divider couplers or a new switch architecture, which can be implemented by using off-the-shelf optical components, and routing is performed on a single channel basis. Since a light-tree is a generalization of a lightpath, the set of light-tree based topologies is a superset of the light-path based topologies. Therefore, an optimum light-tree based topology should perform better than an optimum light-path based topology. The light-tree enables single hop communication between a source to a set of destinations and therefore can significantly reduce the hop distance (in a multi-hop packet switched network 3.8) resulting in better throughput and delay characteristics. In [43], a light-tree based virtual topology design problem is formulated with one of two objective functions: minimize the average hop distance, and minimize the total number of transmitters and receivers in a network. It is shown that an optimum light-tree based virtual topology has smaller average hop distance and requires fewer transmitter/receiver components than the corresponding lightpath based topology to carry the same traffic demand.

3.5. Capacity of Wavelength Routing Networks

Achievable throughput for a wavelength routing network is given by:

$$S = R \times W \times C$$

where W is the number of wavelengths, C is the data rate of each wavelength channel, and R is the *wavelength reuse factor* [44]. The wavelength reuse factor is defined as the maximum number of lightpaths per wavelength for which the blocking probability can be made arbitrarily small if the number of wavelengths is sufficiently large. In other words, the wavelength reuse factor is the maximum number of edge disjoint lightpaths in a physical topology. One way to compare the performance of different topologies is to compare the values of R for uniform traffic. This factor grows with the topological connectedness of the network. This is because it is possible to have more edge disjoint paths in a more complex topology. Therefore, the reuse factor increases with the number of edges in the network [44]. This is because increasing the number of edges will reduce the average path length and improve the wavelength reuse factor. It was shown through simulations [44] that wavelength reuse factor also increases with the number of nodes, N . The reason for this is that the average path length grows roughly as $\log N$ while the number of edges grows with N . Therefore, wavelength reuse factor grows roughly as $N/\log N$. According to these results, it can be concluded that wavelength routing networks are very scalable.

It is also possible to improve the performance of a wavelength routing network with a large number of wavelengths or an increase in the capacity of each wavelength channel. However, channel bit rate and/or number of wavelengths is limited by physical effects [31]. The chromatic dispersion, polarization mode dispersion, and fiber nonlinearities limit the maximum possible rate of each channel. On the other hand, gain bandwidth of optical amplifiers and fiber nonlinear effects such as four wave mixing, and cross phase

modulation, limits the number of wavelength channels in a fiber. Therefore, a significant capacity increase can be supplied through larger amplifier gain bandwidths in a wavelength routing network spanning over long distances.

3.6. Wavelength Requirements

The required number of wavelengths to satisfy a given network traffic demand is an important factor that determines the feasibility of a wavelength routing network. The complexity and cost of wavelength routing devices and amplifiers employed in a network strongly depend on the number of wavelengths they handle. In addition, the number of usable wavelength channels is restricted due to the physical limitations of optical components. Therefore, wavelength is an expensive resource in a WDM network.

In [45] and [46], theoretical lower and upper bounds on the number of wavelengths required to perform *permutation routing* have been derived for static and re-configurable wavelength routing networks. In permutation routing, all sets of connections, where each node is connected to the other node, should be routed.

In a static N node wavelength routing network with S *switching states* (number of possible switch configurations) the number of wavelengths W required to support a traffic set T (set of all *traffic states* (i.e., set of simultaneous sessions)) is given in [45] as:

$$W \geq \left(\frac{|T|}{S} \right)^{\frac{1}{2N}}$$

In a permutation traffic set, there are $|T|=N!$ traffic states. Since, $N! \geq N^N e^{-N}$, at least $\sqrt{N/e}$ wavelengths are required to perform permutation routing in any passive ($S = 1$) wavelength routing network. That is, the lower bound on the number of wavelengths for permutation routing in a passive wavelength routing network is $O(\sqrt{N})$ wavelengths. In [45] and [46], the existence of solutions to the permutation routing problem using $O(\sqrt{N \log N})$ wavelengths for passive wavelength routing networks is also demonstrated. In addition, it was shown in [45] that the required number of wavelengths for an *oblivious* permutation routing requires at least $\lfloor N/2 \rfloor + 1$ wavelengths, and it can be done using $\lfloor N/2 \rfloor + 2$ in a passive wavelength routing network. Oblivious routing is a routing scheme that always assigns the same wavelength to a given connection on a predefined path, regardless of the other connections in the network.

It was shown in [46] that permutation routing in a re-configurable wavelength routing network with W wavelengths requires $O((N \log N)/W)$ generalized switches. Therefore, it is possible to construct a re-configurable wavelength routing network with $O(N)$ generalized wavelength routing switches using only $O(\log N)$ wavelengths for permutation routing. For a given routing scheme, an upper bound on the number of wavelengths, in terms of *congestion* c (number of lightpaths using any edge), and *dilation* d (path length for lightpaths) for the given routing, is also derived as $O(c \min\{d, \sqrt{N}\})$.

The bounds given above are derived by considering only the logical connectivity and represent important information-theoretic bounds on the logical network layer. However, to obtain tighter bounds on the number of wavelengths, the physical topology of a network should be taken into account. In [47], wavelength requirements in arbitrarily connected wavelength routing networks are analyzed. A large number of randomly generated, arbitrarily connected and several real physical network topologies are used to evaluate the required number of wavelengths as a function of physical connectivity. The physical connectivity α

is defined as the ratio of bi-directional links, L , in an N node network with respect to a fully connected network of the same size:

$$\alpha = \frac{L}{L_{FC}} = \frac{2L}{N(N-1)}$$

The lower bound on the number of wavelengths can be obtained for uniform traffic demand (a lightpath for each node pair) between the nodes, which are a combination of an end-node and a wavelength router, as follows. Consider a subset C (network cut) of links whose elimination leaves two disjoint and self-connected sub-graphs of K and $N-K$ nodes. Since each of $K(N-K)$ node pairs should be assigned to a lightpath through these C links, the minimum number of distinct wavelengths for that particular network cut C is given by:

$$W_c = \left\lceil \frac{K(N-K)}{C} \right\rceil$$

Therefore, the theoretical lower bound on the number of wavelengths W is found by evaluating W_c on all possible network cuts, and taking the maximum among them:

$$W = \max_{allC} W_c = \max_{allC} \left\lceil \frac{K(N-K)}{C} \right\rceil$$

It may not be possible to achieve this lower limit, since it does not determine the routing of lightpaths within the network (i.e., it does not take care of the wavelength continuity constraint). However, it can be used as a measure against the efficiency of routing algorithms. If a heuristic algorithm to establish lightpaths is applied on a large number of randomly generated networks, the number of wavelengths for uniform logical connectivity can be analyzed. Analytically it has been shown [47] that wavelength requirements strongly depend on physical connectivity and they are almost independent of network size. In addition, it was shown that the applied lightpath allocation algorithm yields the number of wavelengths equal or very close to the lower limit, and it is equal to the number of channels in the mostly loaded links. Therefore, wavelength converters do not lead to a reduction in wavelength requirements. Instead of using wavelength converters, the selective replacement of heavily loaded links with multi-fiber connections may lead to a reduction in W .

3.7. Routing and Wavelength Assignment

The *physical topology* of a wavelength routing network consists of end-nodes, wavelength routers, and the fibers connecting them. The lightpaths are set up between the end-nodes over this physical topology, and constitute a *logical topology*. Each lightpath is assigned a path through the network and a wavelength on that path. Finding routes for the lightpaths through the physical topology and assigning wavelengths to these lightpaths is called the *routing and wavelength assignment problem* (RWA) [48].

A similar routing problem arises in circuit switched networks, and it has been extensively studied. In these networks, the connections are routed by selecting a path, such that there is a circuit available to accommodate the call in every link on the path. However, in wavelength routing networks, in addition to this constraint, the wavelength continuity constraint should be satisfied. That is, a lightpath should be assigned to the same wavelength on every link in the path, and lightpaths sharing the same link should be assigned to different wavelengths. Note that if optical wavelength converters are employed in the wavelength routers, the RWA problem can be made equivalent to the routing problem in circuit switched telephony networks.

Depending on whether lightpath requests are known initially and fixed over time or not, routing and wavelength assignment schemes can be classified into two categories: *static* and *dynamic*.

In static RWA, all the lightpath requests between end-node pairs are known initially. This is the case for large transport networks in which the planning of the network is made based on an aggregate demand pattern and its forecast future values. Therefore, individual requests are accommodated on provisioned routes during network planning. If the bandwidth requirements for individual connection requests are much less than the bandwidth of a single lightpath, it is possible to use lightpaths to carry electronically multiplexed streams of traffic from many different users. In such a network, end-nodes will be electronic switches such as SONET/SDH cross-connects, ATM switches, etc. In these networks, the number of lightpaths between end-node pairs may remain fixed over time with only rare changes in lightpath allocations to follow slowly changing mean traffic requirements time.

In dynamic RWA, lightpath requests between end-nodes are assumed to arrive at random times and have random holding times. That is, lightpath requests are established on demand. This is the case for data communication networks in which connections require large bandwidths or lightpaths are used for multiplexed packet based traffic. In such networks, end-nodes may correspond to individual workstations or IP routers. Therefore, lightpath requirements may vary frequently over time. For this reason, routing is done individually for each lightpath request to efficiently use network resources.

Typically, in transport networks or WANs, the traffic demand between the end nodes remains almost fixed over time, and in data networks or LANs traffic demand frequently changes over time. Therefore, static RWA can be seen as the primary case for today's wavelength routing networks, which are only suitable for MAN/WAN distances due to their high costs. However, an important portion of the traffic flowing through wide-area networks will be computer communications in the near future. In addition, as the price of optics falls, wavelength routing networks may have a widespread use in LAN applications. Therefore, in a realistic network, a combination of static and dynamic RWA may be employed.

3.7.1. Static Routing and Wavelength Assignment

Several integer linear program formulations have been proposed for optimally determining routes and assigning wavelengths for lightpath requests. Generally, these formulations represent multi-commodity flow formulations, and the problem size grows much faster than the size of the network. Therefore, some approximate solutions or heuristic algorithms are proposed for solving the RWA problem in large networks.

3.7.1.1. Integer Linear Program Formulations

According to whether wavelength converters are employed or not in a wavelength routing network, there are two types of lightpaths [49]. In wavelength continuous wavelength routing networks, each lightpath is assigned to a fixed wavelength, and is therefore called a *wavelength path* (WP). The RWA in these networks can be called *WP-routing*. If wavelength converters are employed in wavelength routers, a lightpath can be assigned to different wavelengths on different links along its route. Therefore, such lightpaths can be called *virtual wavelength paths* (VWP), and RWA in these networks can be called *VWP-routing*.

In both WP-routing and VWP-routing, each lightpath is assigned to a route and a wavelength(s) along this route. In these routing problems, some constraints should also be satisfied. In VWP-routing, the number of lightpaths passing through a link should be smaller than the capacity of that link. The capacity of a link is given by the number of wavelengths in each fiber multiplied by the number of fibers on the link. In WP-routing, in addition to this constraint, the wavelength continuity constraint should be satisfied. For

this reason, the number of lightpaths that share the same link and are assigned to the same wavelength should be lower than the number of fibers on that link. For a given fixed physical topology, due to these constraints, it may not be possible to route all lightpath requests. Therefore, the problem is formulated as an integer linear program to maximize carried traffic (number of lightpath requests accommodated) in a given network.

In [49], two types of formulations are considered for both WP and VWP routing: *route formulations* and *flow formulations*. In route formulations, all routes between all end-node pairs are enumerated, and the number of times a route is used is determined. In flow formulations, the basic decision variables are the flows on the links generated through each end-node pair.

In these formulations, the physical topology of the network is modeled as a unidirectional graph, $G = (V, E)$, where $V = \{v_1, v_2, \dots, v_n\}$ is the set of wavelength routers/end-nodes and $E = \{e_1, e_2, \dots, e_m\}$ is the set of fiber links. In this graph each fiber link may contain one or more fibers, therefore, a capacity vector $D = [k_j]_{m \times 1}$ is defined to represent the capacity of fiber links. In this vector, each k_j is equal to the number of fibers on link j multiplied by the number of wavelength channels on each fiber. To ease formulation, the source-destination pair set (sd-pair set) $S = \{v_i v_j \mid 1 \leq i < j \leq n\}$ with size s is used to represent end-node pairs. Then, lightpath requests can be represented by a demand vector $D = [d_i]_{1 \times s}$ where d_i represents the number of lightpaths that are to be set up between the sd-pair i .

In route formulations, all possible cycle-free routes between all sd-pairs are determined and the set $R = \{r_1, r_2, \dots, r_r\}$ is formed by these routes. In accordance with set R , the route-sd-pair incidence matrix Q and route-fiber-link incidence matrix B are formed as:

$$Q = [q_{ij}]_{r \times s} \quad q_{ij} = \begin{cases} 1, & \text{if route } i \text{ is incident to sd - pair } j \\ 0, & \text{otherwise} \end{cases}$$

$$B = [b_{ij}]_{r \times m} \quad b_{ij} = \begin{cases} 1, & \text{if edge } e_j \text{ is used on route } i \\ 0, & \text{otherwise} \end{cases}$$

In VWP routing using route formulation, the ILP variables can be represented by the routing vector $F = [f_i]_{1 \times r}$ where f_i represents the number of times a route is used. Therefore, the route formulation for VWP routing that maximizes the carried traffic can be given as:

$$\begin{aligned} & \max \sum_{i=1}^r f_i \\ & \text{subject to:} \\ & \text{(demand is partly or completely satisfied)} \\ & F \cdot Q \leq D \\ & \text{(number of lightpaths sharing} \\ & \text{each link is limited to link capacity)} \\ & F \cdot B \leq K^T \end{aligned}$$

In WP routing using route formulation, the ILP variables can be represented by the route-wavelength matrix $W = [w_{ij}]_{r \times \lambda}$ where w_{ij} represents the number of paths using route r_i and wavelength j , and λ is the number of wavelength channels on each fiber. Therefore, the route formulation for WP routing that maximizes the carried traffic can be given as:

$$\begin{aligned} & \max \sum_{i=1}^r \sum_{j=1}^{\lambda} w_{ij} \\ & \text{subject to:} \\ & \text{(demand is partly or completely satisfied)} \\ & \mathbf{1}_{\lambda} \cdot \mathbf{W}^T \cdot \mathbf{Q} \leq D \\ & \text{(number of lightpaths using same wavelength} \\ & \text{and sharing the same link is limited to} \\ & \text{the number of fibers on that link)} \\ & \mathbf{W} \cdot \mathbf{B} \leq \frac{1}{\lambda} \mathbf{1}_{\lambda}^T \mathbf{K} \end{aligned}$$

where $\mathbf{1}_{\lambda}$ is a $1 \times \lambda$ vector in which all elements are 1.

In flow formulations, the basic decision variables are the flows on fiber links generated by each sd-pair. Variables in VWP routing are represented by the routing matrix $X = [x_{jk}]_{m \times s}$ where x_{jk} is equal to the amount of traffic flow from sd-pair k on link j . Therefore, the flow formulation for VWP routing that maximizes the carried traffic can be given as:

$$\begin{aligned} & \max \sum_{j=1}^s p_j \\ & \text{subject to:} \\ & \text{(demand is partly or completely satisfied)} \\ & P \leq D \\ & \text{(for each sd - pair the number of lightpaths} \\ & \text{routed and flow conservation must be valid} \\ & \text{in every vertex)} \\ & \sum_{a_j \in \alpha(v_i)} x_{jk} - \sum_{a_j \in \beta(v_i)} x_{jk} = \begin{cases} p_k, & \text{if } v_i = \text{src. of } sd \text{ pair } k \\ -p_k, & \text{if } v_i = \text{dst. of } sd\text{- pair } k \\ 0, & \text{otherwise} \end{cases} \\ & \text{(total flow on any edge does not} \\ & \text{exceed its physical capacity)} \\ & \sum_{k=1}^s x_{jk} \leq k_j \end{aligned}$$

where $P = [p_j]_{1 \times s}$ represents the routed traffic where p_j is the number of lightpaths routed between sd-pair j , and $\alpha(v_i)$ and $\beta(v_i)$ represent the set of links which have v_i origin and as destination.

The variables in WP routing using flow formulation are represented by the route-wavelength matrix $Y = [y_{ijk}]_{\lambda \times m \times s}$ where y_{ijk} is equal to the amount of traffic flow from sd-pair k on link j on wavelength i . Therefore, the flow formulation for VWP routing that maximizes the carried traffic can be given as:

$$\begin{aligned}
 & \max \sum_{z=1}^{\lambda} \sum_{j=1}^s t_{zk} \\
 & \text{subject to:} \\
 & \text{(demand is partly or completely satisfied)} \\
 & \sum_{z=1}^{\lambda} t_{zk} \leq d_j \\
 & \text{(for each sd - pair the number of lightpaths} \\
 & \text{routed and flow conservation must be valid} \\
 & \text{in every vertex)} \\
 & \sum_{a_j \in \alpha(v_i)} y_{zjk} - \sum_{a_j \in \beta(v_i)} y_{zjk} = \begin{cases} t_{zk}, & \text{if } v_i = \text{src. of sd - pair } k \\ -t_{zk}, & \text{if } v_i = \text{dst. of sd - pair } k \\ 0, & \text{otherwise} \end{cases} \\
 & \text{(capacity constraints)} \\
 & \sum_{k=1}^s y_{zjk} \leq \frac{k_j}{\lambda}
 \end{aligned}$$

where $T = [t_{zk}]_{\lambda \times s}$ represents the routed traffic where t_{zk} is the number of lightpaths routed between sd-pair j on wavelength z .

The objective of all the above formulations is the maximization of the number of lightpath requests accommodated in a given physical topology. There are other formulations with different objective functions proposed for both WP-routing and VWP-routing. For example, in [50], VWP-routing is formulated as an integer linear program (similar to flow formulation) with the objective function being to minimize the flow in each link. This corresponds to minimization of the number of wavelength channels required in each fiber (i.e., number of wavelengths required) to carry all the lightpath requests over a known physical topology. An alternative approach, which tries to minimize the total facility cost for a given physical topology and given lightpath demands, is proposed in [51] for both VWP-routing and WP-routing. In formulations, the facility cost is obtained from transmission, multiplexing, and cross-connection costs. These costs are proportional to fiber length, total number of fibers and total number of optical cross-connects used on fiber links and wavelength routers. In addition to routing given lightpath demands, it is also possible to include fiber topology (physical topology) design in formulations. In [52], fiber topology and the optical path layer (virtual topology) design problem to minimize the total cost of the network for a given static traffic demand is formulated. Both VWP-routing and WP-routing considered and the location of wavelength routers, a set of candidate links between these routers, and the demand between each sd-pair is given initially.

In [49], route and flow formulations for VWP-routing and WP-routing are compared, and computational requirements are expressed through the number of variables and constraints. Table 3 compares the problem sizes of route and flow formulations given in this section. It can be seen from the table that the size of the VWP-routing problem is independent of the number of wavelengths, whereas the WP-routing problem grows quadratically with the number of wavelengths. On the other hand, the number of variables is proportional to the number of routes in route formulations. Therefore, the number of variables increases exponentially with network size for highly connected networks. Although the number of variables is much lower in flow formulations, the number of constraints grow exponentially with the size of the network.

Since both route and flow formulations are computationally intensive for large networks, some approximation methods are proposed to solve the ILP for large networks. For example, in [50], the routing and wavelength assignment problem is decomposed into a number of sub-problems, which are solved independently. First, the RWA problem is formulated as an integer linear problem similar to VWP-routing using flow

formulations. Then, ILP is pruned by tracking a limited number of alternate breadth-first paths between sd-pairs to reduce the problem size. Instead of solving ILP, the problem is solved as a linear program (LP) and a probabilistic technique (called *randomized rounding*) is applied to LP the solution to obtain integer solutions. Once paths for each lightpath are found, *graph-coloring algorithms* are used to assign wavelengths to those lightpaths. It is shown in [50] that the number of wavelengths required for this approximate solution is asymptotically close to the lower bound obtained through the LP solution.

Table 3. Problem Size of ILP Formulations

	Route Formulations		Flow Formulations	
	VWP-routing	WP-routing	VWP-routing	WP-routing
Number of Variables	r	$rx\lambda$	mxs	$mxx\lambda$
Number of Constraints	$m+s$	$mx\lambda+s$	$m+nx\lambda+s$	$mxx\lambda+2s$

3.7.1.2. Heuristic Algorithms

It is shown that [38] both VWP-routing and WP-routing are NP-complete. Therefore, several heuristics are proposed for VWP-routing and WP-routing with various objective functions to solve the RWA problem for large networks in acceptable processing time.

In [47], a heuristic algorithm is proposed for lightpath allocation in an arbitrarily connected wavelength routing network. Every end-node pair is assigned to a single lightpath through the network, and the algorithm tries to minimize the number of wavelength channels required in fibers to route this traffic over the given physical topology. In this algorithm, first, the shortest path routes are determined between each end-node pair and these routes are assigned to lightpath requests. In this way, total and average transit traffic through the wavelength routers is minimized. Since usually more than one shortest path exists between each end-node pair, it is possible to balance the number of paths among all links by choosing routes properly from these alternatives. Therefore, substitutions of alternative shortest paths are carried out for lightpaths if the number of channels of the most loaded link in the alternative path is lower than the previous one. When there are no substitutions possible, the routing of lightpaths are completed, and the assignment of wavelengths to these paths takes place. Wavelength assignment is done in such a way that wavelengths are assigned to some indexes, and lightpaths with longer paths are assigned to the smallest index wavelength available through its route before other lightpaths. The reason for this longer path policy is that it is harder to find a free wavelength on more links. It is shown that this algorithm yields wavelength requirements that are very close to the lower limit given in Section 3.6. Moreover, it was observed that in all analyzed networks the number of wavelengths required is equal to the number of lightpaths on the most loaded link(s), implying wavelength converters do not lead to a reduction of wavelength requirements. Instead of using wavelength converters, replacement of heavily loaded links with multiple fibers leads to a reduction in wavelength requirements.

Another heuristic algorithm, called the *Heuristic Routing and Wavelength Assignment algorithm* (HRWA), which minimizes the required number of wavelengths is proposed in [49]. The algorithm starts with searching for the shortest paths for each sd-pair and selecting the shortest routes that minimize wavelength requirements. Then, the number of required wavelengths is decreased by rerouting a number of lightpaths. The next step is repeated until no further improvement is possible. The simulations show that HRWA

performs well in terms of calculation time and maximization of the wavelength reuse as compared to ILP solutions.

Two similar heuristic algorithms (that use rerouting of lightpaths to minimize an objective function) for WP-routing and VWP-routing are proposed in [41]. In these algorithms, each link is composed of multiple fibers, and the algorithms try to minimize optical path cross connect system scale (i.e., the total number of fiber ports required in each node). That is, the objective is the minimization of the average number of fibers handled at wavelength routers. In some networks this is required for practical (or cost effective) realization of wavelength routers. In the VWP scheme, lightpaths are initially set up so that they are evenly distributed within the network (i.e., every link should have an equal number of lightpaths). Then, the links with the most inefficient wavelength utilization (i.e., having a large number of lightpaths using link *mod* number of wavelengths in each fiber) are determined. Then, the lightpaths that use the maximum number of such links are re-routed. This re-routing iteration is done a certain number of times until the algorithm is completed. Once the routes are determined, the fiber requirements for each link can be determined as $\lceil \text{number of lightpaths} / \text{number of wavelengths} \rceil$. The WP-routing algorithm starts with the VWP-routing algorithm to determine the routes for lightpaths. Then, all the lightpaths are divided into a minimum number of layers in such a way that any two lightpaths in a layer do not share any link. Then layers are assigned to a layer number randomly and wavelengths are assigned according to the layer number (i.e., assigned wavelength = Layer number *mod* number of wavelengths). Finally, all these steps for different set of initial routes are repeated a number of times, and the assignment with the lowest value of the objective function is selected as routing of lightpaths. Simulations show that the WP-routing scheme incurs large optical path cross connect system scale than VWP-routing scheme. Moreover, the difference between WP-routing and VWP-routing schemes increases as the number of wavelengths increases. This is because, in the WP scheme, many more wavelengths remain unassigned on links as the number of wavelengths multiplexed in a single fiber increases.

3.7.2. Dynamic Routing and Wavelength Assignment

In dynamic RWA, lightpath requests between end-nodes arrive at random times and have random holding times. Therefore, each lightpath is set up and torn down individually while the other lightpaths exist in the network. The RWA in such a network can be decomposed into two sub-problems [30]. The first sub-problem is finding a route through which the lightpath is formed between the end-nodes, and the second sub-problem is the assignment of wavelength(s) to that lightpath. According to the availability of wavelength converters, the RWA problem can be classified into two types as defined previously: VWP-routing and WP-routing. Since the wavelength continuity constraint should be satisfied in WP-routing, the wavelength assignment sub-problem is much harder in WP-routing than the wavelength assignment in VWP-routing. Therefore, many different algorithms are proposed for assigning wavelengths to lightpaths in such a way that the blocking probability due to wavelength conflicts for future requests are minimized. On the other hand, in VWP-routing, minimizing the number of wavelength converters used for a lightpath is important (for the efficient use of network resources). To get better performance, some algorithms are proposed that try to solve the routing sub-problem and the wavelength assignment sub-problem simultaneously. However, in such algorithms computations become much more complex.

The dynamic RWA algorithms can be classified as *static* or *adaptive* [40]. In static algorithms, RWA procedure does not change with time. That is, possible route-wavelength pairs are determined in a predefined order through static algorithms. On the other hand, adaptive algorithms use network state information at the time of request arrival to find a route and wavelength for a lightpath request. Therefore, in dynamic

algorithms, all possible route-wavelength pairs can be sought for the optimal routing of lightpath for an objective function.

The fixed or alternate routing and *first-fit* or *random* wavelength assignment [30] are the most commonly used static algorithms. In fixed routing, all sd-pairs are assigned to a single path (usually the shortest path between the end-nodes). If a lightpath can not be established on this path (i.e., there is no common wavelength along the path), the lightpath request is blocked. Otherwise, a wavelength is selected among the idle wavelengths (on all links along the path) to set up the lightpath. In alternate routing, each sd-pair is assigned to more than one route to establish lightpaths. Therefore, these routes are determined in a predefined order to establish the lightpath. In both fixed and alternate routing, if a route with one or more idle wavelengths (idle along the route) is found, first-fit or random wavelength assignment methods can be used for wavelength selection. In the random method, one of the available wavelengths is chosen from the set of available wavelengths randomly. In the first-fit method, wavelengths are assigned to some index values ($\lambda = 1..W$) and the wavelength with the smallest index value is chosen among the available wavelengths.

In [40], a method for obtaining approximate blocking probabilities for fixed and alternate routing using first-fit wavelength assignment is developed. It is shown that alternate routing with only two alternate paths between each sd-pair results in a large reduction in the blocking probability compared to fixed routing. This is due to fact that there are more wavelength-route alternatives in alternate routing to set up the lightpath. Moreover, performance improvement is more pronounced if the number of wavelength channels in fiber links is large. It is also shown that the blocking performance improves dramatically with the use of multiple fibers in the links (i.e., in multi-fiber networks). In [53], first-fit and random wavelength assignment methods with shortest path (fixed) routing are compared through simulations, and an analytical model is developed for analyzing the blocking probability of the first-fit algorithm. It is shown that the first-fit algorithm performs much better than the random algorithm at low loads, and the performance difference is marginal at higher loads. This is because, at lower loads, most of the request blockings are caused by wavelength conflicts. Therefore, blocking probability is reduced with the first-fit algorithm due to the packing of lightpaths in the smaller indexed wavelengths (i.e., higher indexed wavelengths are reserved for future requests). On the other hand, at higher loads, most of the requests are blocked due to insufficient capacity. Therefore, the wavelength assignment algorithm has little effect on performance at high loads. It is also shown that the first-fit algorithm performs better when the number of fibers per link is small in multi-fiber networks.

If information about global wavelength usage is available at the time of routing, it may be possible to reduce further the blocking probability for future requests (compared to first-fit or random algorithms) by finding a good route-wavelength pair. The *pack (most-used)* and *spread (least-used)* adaptive wavelength assignment algorithms [40] are proposed for this purpose. The pack algorithm tries to assign the most utilized wavelength to the lightpath. That is, among the available wavelengths, the one that is used on the most links over the network is assigned to the lightpath. On the other hand, in a spread algorithm, the least utilized wavelength is assigned to the lightpath. Therefore, the load is uniformly distributed over the wavelength set. In [40], blocking performances of pack, spread, random and first-fit wavelength assignment algorithms with adaptive unconstrained routing (AUR) are compared. In AUR, all possible routes between a sd-pair are sought in the routing. The simulations show that, the pack scheme has the best performance followed by the random and spread schemes. When the number of wavelengths is large, the pack algorithm outperforms the other two algorithms by a significant margin. The results also indicate that the performance of first-fit is very close to that of the pack algorithm. This is because the first-fit approximates the pack by assigning most lightpaths to wavelengths with smaller indexes.

The *least-loaded routing* (LLR) algorithm proposed in [53] jointly selects the least-loaded route-wavelength pair over k alternate routes (shortest paths) between sd-pairs. Therefore, the residual capacity over all wavelengths and over k shortest routes is maximized. To do this, LLR chooses the route p and wavelength j pair that achieves

$$\max_{p,j} \min_{l \in p} M_l - A_{lj}$$

where p denotes the routes in the alternate route set, j denotes the wavelengths, l denotes the links, M_l denotes the number of fibers on link l , and A_{lj} denotes the number of fibers for which wavelength j is utilized on link l . The LLR algorithm can be adapted to VWP routing by choosing the route p that achieves

$$\max_p \min_{l \in p} K M_l - \sum_{j=1}^K A_{lj}$$

where K is the number of wavelength channels in each fiber. Simulations show that in both WP-routing and VWP-routing, the LLR algorithm achieves much better blocking performance compared to fixed-routing (shortest-path) algorithms. Moreover, the performance difference between WP-routing and VWP-routing gets larger as the number of alternate routes increases. This is because alternate routes may be longer than the shortest route, and the probability of a wavelength conflict increases along long routes.

An alternative approach called *least congested path* (LCP) routing is proposed in [20] for dynamic RWA. In LCP, the lightpaths are routed on the least congested path, and first-fit wavelength assignment is done. In [20], the LCP is compared using the static RWA with ILP formulation. The same set of lightpaths is routed over the same physical topology, and lightpaths arrive randomly in the dynamic RWA case. The results show that congestion over all the links and the number of wavelengths required are very close to each other for dynamic and static RWA. That is, the wavelength requirements for LCP and the optimal routing are close to each other.

In [38], [54], and [55], graph based methods for finding optimal routes and wavelengths for lightpaths using shortest path routing are proposed. In these methods, a graph representing the physical topology of the network with link costs obtained from the state of the network and device usage (i.e., wavelength converters, etc.) at the time of routing is developed. Shortest path algorithms are applied to determine the best solution on this graph. This solution is then used to obtain the optimal route-wavelength pair on the physical topology. In [38], an auxiliary graph is created to facilitate the representation of conversion cost and channel, cost. In this graph, the input and output ports of wavelength routers are represented by multiple vertexes representing each wavelength channel and these vertexes are connected by the edges representing the wavelength-link pairs in the physical topology. Then the input and output vertexes in a router are connected to each other directly by an edge for the same wavelength or by the edges between the vertexes of different wavelengths to represent wavelength converters. Finally, edges are assigned to weights that represent its status (wavelength-link usage information), and wavelength conversion cost (number of remaining converters in a router). In this model, two wavelength sharing approaches are considered: share-per-node and share-per-link. Therefore, depending on how the converters shared, weights are assigned to converter edges differently. Finally, Dijkstra's algorithm is used to solve the routing problem. In [54], a similar approach is used to construct a graph that facilitates routing and wavelength assignment by virtually separating the wavelengths into different paths. This approach is called the *layered graph approach*. In

this model, limited-range wavelength conversion is considered. Therefore, the converter edges are created between the input-output ports of wavelength routers for different wavelengths by considering the conversion range of converters (i.e., some edges in the previous model disappear due to limited conversion range). Then the shortest path routing with first-fit wavelength assignment (the smallest indexed wavelength among the shortest paths is chosen) is applied by setting the hop count as the routing cost. In [55], a fast and practical algorithm is presented to optimally route lightpaths, taking into account both the costs of wavelengths on the links and the cost of wavelength conversion. To do this, a *wavelength graph* (WG) (similar to previous graphs) is constructed in such a way that the minimum weight path in this graph corresponds to minimum cost routing and wavelength assignment in the physical topology. In WG, the shortest paths are sought by using an algorithm called SPAWG, and a found path is mapped back to the network to obtain the minimum cost route-wavelength pair. It was proven that the running time of this algorithm is the best possible over all known related practical algorithms. It is claimed that this algorithm is a good candidate for efficient practical implementation due to its simplicity and fast running time.

The algorithms introduced above all try to route the lightpaths without disturbing other lightpaths existing in the network. For this reason, although there is enough capacity available in the network, some of the lightpath requests are blocked due to wavelength conflicts. To overcome this problem, some existing lightpaths can be re-routed to accommodate new requests. In [56], re-routing and minimization of incurred disruption due to re-routing using the move-to-vacant wavelength-retuning (MTV_WR) algorithm is considered. In MTV_WR, a lightpath is moved to a vacant wavelength on the same path. The performance results show that call blocking probability is reduced by an average of 30% with rerouting average of only 1.3 lightpaths in a 21-node test network.

While all the works reviewed so far in this section are all *centrally managed*, that is, assume that a central controller is present and has access to all necessary information for solving the RWA problem, a recent proposal has introduced a distributed solution [57]. Based on the classical Bellman-Ford algorithm, Başbuğoğlu has implemented two realistic algorithms that achieve minimum congestion and minimum wavelength conversion respectively. His work also includes a simulation-based demonstration of the performance of the proposed algorithms.

3.8. Packet Switched Wavelength Routing Networks

In packet switched networks, each end-node must be able to transmit/receive successive packets to/from different destinations/sources possibly on different wavelengths. To support packet switching in a wavelength routing network, there are two possibilities: each sd-pair is assigned to a separate lightpath for packet communication or packet switching is done at wavelength routers. The first approach may not be practical for large networks due to two reasons. First, the number of wavelengths available imposes a limit on the number of lightpaths that can be set up on a network. Second, each end-node can be the source and sink of only a limited number of lightpaths determined by the number of transmitters and receivers it has. Therefore, logical topologies can be designed to carry the packets in a multi-hop manner efficiently for a given traffic demand and physical topology. On the other hand, the second approach (i.e., packet switching at wavelength routers) suffers from the difficulties of implementing optical processing and buffering devices, as well as fast switching devices.

3.8.1. Logical Topology Design

To design an efficient logical topology to carry packet switched traffic in a wavelength routing network, traffic demand between the end-nodes should be determined. The traffic demand can be obtained from the long-term averages of the number of packets communicated between each sd-pair. Once the demand matrix is determined, the problem is to design an optimal logical topology according to some objective function (such as link congestion, or delay) and embed this logical topology in a given physical topology. The logical topology design and routing (embedding in physical topology) problem can be formulated as an integer linear program (like optimal RWA in circuit switched wavelength routing networks). Since the solution of this ILP problem is computationally difficult some heuristic design algorithms can be employed for logical topology design.

In [58], the logical topology design and routing problem is formulated as a *mixed integer linear program* (MILP). The objective is to minimize the maximum congestion on any link of the logical topology while constraining the average delay seen by each sd-pair and degree of logical topology. That is, the maximum number of packets flowing through each virtual link is minimized while the propagation delay experienced by a packet is limited to some extent. The minimization of maximum link congestion is an important design criterion because a network with smaller maximum link congestion allow its traffic demand to increase by a larger factor (i.e., carry much more traffic) for the same physical topology. Delay is also an important factor because ignoring the delay constraints may cause fairly convoluted logical topologies with very long delays. An informal description of the logical topology design problem can be given as follows [58]:

$$\min \max_l \lambda_l$$

(where λ_l : number of packets flowing through link l)

subject to:

- Each logical link corresponds to a lightpath in the physical topology, and the wavelength continuity constraint is satisfied.
- Every end-node can be the source/destination of at most K lightpaths, where K is the number of transmitter/receivers at that node.
- Traffic is routed so that the traffic flows between each sd-pair are conserved at each node.
- For each sd-pair, the propagation delay is at most some multiple of the shortest-path propagation delay in the physical topology.

Since the MILP is computationally intractable, the problem is split into two sub-problems as *logical topology design* and *routing*. The logical topology design sub-problem is solved through heuristic algorithms, whereas the routing sub-problem is solved by a linear program. For this purpose three different heuristic topology design algorithms are proposed in [58]: The heuristic topology design algorithm (HLDA), the minimum-delay logical topology design algorithm (MLDA), and the traffic independent logical topology design algorithm (TILDA). The HLDA attempts to place the logical links between sd-pairs in order of descending traffic. Therefore, the congestion is lowered by routing most of the traffic in one hop without considering delay constraints. Unlike the HLDA, the MLDA is capable of satisfying the tightest delay constraints that are physically realizable by adding some logical links to the links found by HLDA to route

packets on the shortest possible physical path between every sd-pair. The TILDA attempts to minimize the number of wavelengths required by ignoring traffic demand. This may be an appropriate choice if traffic is unknown or known to be uniform.

In [59], two methods are proposed for logical topology design to minimize the maximum link congestion in a packet switched wavelength routing network: *LP-based One-Hop Traffic Maximization Scheme* (OHTM) and *Link Elimination via Matching Scheme* (LEMS). The OHTM uses a linear program formulation that maximizes the total one hop traffic while maintaining the connectivity of a logical topology. That is:

$$\begin{aligned} & \max \sum_i \sum_j x_{ij} t_{ij} \\ & \text{subject to :} \\ & \sum x_{ij} = d \quad \forall j \end{aligned}$$

where t_{ij} is the traffic demand between end-nodes i and j , d is the degree of each node (i.e., number of transmitter/receiver pairs on the end-node) and x_{ij} are the variables to denote the logical connectivity between i and j , i.e.,

$$x_{ij} = \begin{cases} 1 & \text{if there is a logical link from node } i \text{ to } j \\ 0 & \text{otherwise} \end{cases}$$

In order to guarantee the connectivity of the logical topology, one unit of flow from node 1 to every other node is assumed, and flow conservation constraints are added to the above formulation to ensure that the network supports these flows.

The LEMS is a heuristic algorithm that starts with a fully connected virtual topology and eliminates lightly loaded links until a topology with the desired node degree is obtained. To do this, first, a complete bipartite graph with each partition containing all the nodes is created. The weights of the edges in this graph are set to the traffic demand between the corresponding node pairs. Then, minimum weight perfect matching is done on the edges, and matched edges are eliminated from the graph. Then, traffic on the eliminated edges is re-routed on shortest paths, and weights are updated correspondingly. These matching and elimination steps are repeated until nodal degree constraints are satisfied. Finally, the resultant logical topology is embedded in the physical topology. If the number of wavelengths required for embedding is larger than that available, the lightpaths requiring extra wavelengths are rerouted on minimum congestion routes. In [59], OHTM, LEMS and random topology (a randomly created logical topology that satisfies degree constraints) are compared. It is shown that OHTM performs best and has 5-30% better maximum link congestion values than a random topology. It is observed that LEMS performed the worst as the usage of shortest path routing (rerouting of eliminated edges) is not effective in reducing maximum link congestion. However, if LP based routing is done on the resultant logical topology, the performance can be improved significantly.

3.8.2. Wavelength Routing Packet Switches

The wavelength routers discussed so far are designed to route signals on different wavelengths at input ports to output ports without taking care of the information carried by that signal. The switching matrix of the router is determined by an external control such as a central controller. However, in a packet-switching environment the information on the packets determines the output port in routers. Therefore, to support packet switching in wavelength routers the addressing information on each packet should be extracted

according to this information, the corresponding output port should be selected (switched) in a short time period. Therefore, recognition of the packets, and fast switching, is required in a wavelength routers to support packet switching. Actually, the main problem in the implementation of wavelength routing packet switch is not only fast switching. In a packet switched environment, a buffering mechanism is required to resolve the resource contention when multiple packets of the same wavelength contend for the same output port of the router simultaneously. However, buffering in the optical domain is not an easy problem.

In many studies [60], [61], [62], re-circulating loops and optical delay lines are proposed to solve buffering problem. A fiber delay-line is a long piece of fiber that introduces propagation delays in the order of packet transmission times. The staggering switch, which is an almost all-optical switch architecture that employs fiber delay-lines for storage, is proposed in [60]. The original switch architecture supports single wavelength operations and is based on two stages: a scheduling stage and a switching stage. These stages are electronically controlled optical cross-connects. The scheduling stage is $n \times m$ and the switching stage is $m \times n$ where $m > n$. The scheduling stage is connected to the switching stage by m delay lines $d_i, i = 1..m$ and the delay introduced by delay line d_i is equal to i packets. Packets at the input ports are detected by splitter detector blocks and the header information is extracted from the packets. These packets can be formed in two parts to support transparent communication between the end-nodes: header and payload. The header is transmitted at a fixed bit rate with a common format. The payload can be a fixed duration signal where information is carried by the network regardless of its rate and format. The header information is used by an electronic control block to select proper delay line and output port by setting the switches on scheduling and switching stages properly. If two packets on different input ports contend for the same output port, the control block sends these packets to different delay lines to resolve any contention. The staggering switch may be extended in the wavelength domain to obtain a packet switched WDM wavelength router. To have a wavelength router with n input/output ports with k wavelength channels on each port, each input port is demultiplexed into k wavelength channels. Then, n channels of the same wavelength are grouped together for switching in a single $n \times n$ switch (similar to Figure 15 with optical cross connects replaced by staggering switches). The outputs of the switches are multiplexed into n output ports.

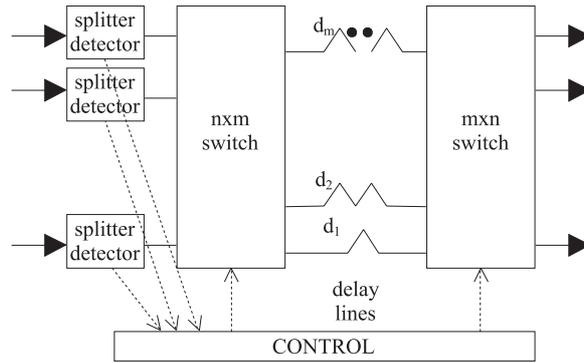


Figure 21. Staggering Switch Architecture

There are two important switch performance criteria for the staggering switch: cell loss ratio and packet latency. Since the number of delay lines is limited, there is a probability of packet loss in a switch (especially under bursty traffic conditions) [60]. As expected, increasing the number of delay lines lowers the loss probability. However, increasing the number of delay lines increases the complexity of the switch and reduces the compactness. The required number of optical delay lines can be reduced considerably by using tunable optical wavelength converters. In [63], three different switch architectures are proposed with buffers

realized by fiber delay-lines and with tunable wavelength converters to address free space in the buffers. By using wavelength converters to assign packets to unused wavelengths in the fiber delay-line buffers, it is shown that the number of fiber delay lines can be reduced considerably [63], [64].

3.9. Survivable Wavelength Routing Networks

Since each fiber and wavelength router accommodates a large amount of traffic in wavelength routing networks, the amount of bandwidth lost due to a fiber link or wavelength router failure is much larger than other types of networks. Therefore, survivability is indispensable.

There are several studies [41], [51], [52], [65] that consider logical topology design and physical resource assignment to maintain survivability. In these studies, static routing and wavelength assignment problems are formulated to route a predefined set of lightpath requests and corresponding set of restoration lightpaths for single link failure. In [51], [52], and [65], the routing and spare capacity planning problems are formulated as integer linear programs. Heuristic algorithms are also proposed for this purpose in [41] and [52].

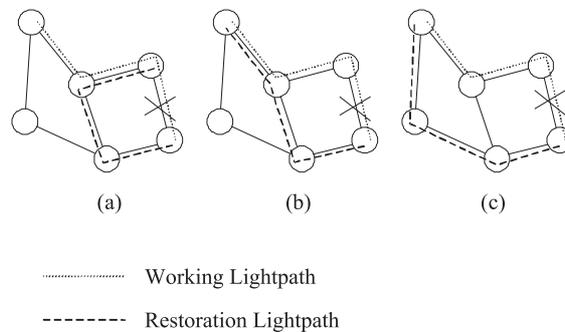


Figure 22. Restoration Strategies [52] (a) Link Restoration (b) Path Restoration (c) Path Restoration with Link-Disjunct Route

Protection against failures requires many spare resources. However, in meshed networks, by sharing spare resources among several restoration lightpaths, it is possible to reduce the amount of required spare capacity. Therefore, we need some algorithms to assign spare capacity efficiently. There are three rerouting strategies proposed for single link failures [52] (Figure 22): *Link restoration* (LR), *path restoration* (PR), and *path restoration with link-disjunct route* (PRd). In LR, the traffic between the end-nodes of a failed link is rerouted. Therefore, this is a quick rerouting method. In PR, the broken traffic between the end-nodes of the affected lightpaths is rerouted. Therefore, this method requires much lower spare capacity compared to LR. In PRd, the lightpaths are rerouted along a pre-assigned link-disjunct route. Therefore, the restoration process can be started immediately after a failure without knowing the exact location of the failure. For path restoration schemes, it is also possible to reuse the released capacity due to rerouting of working paths.

4. Issues of Recent and Current Research In Optical Networking

Concerning complexity and scalability, all optical networking technologies, RWA and restoration algorithms, must be scaled to a large number of wavelengths and nodes. The fairness problem, optimal wavelength converter placement, sparse and limited wavelength conversion with dynamic traffic demand are all to be worked on [30].

The application of centralized, distributed or hybrid algorithms is to be determined considering the advantages and disadvantages of each. Centralized algorithms do not require the implementation and maintenance complexity that distributed schemes typically need. Using centralized algorithms, optimized solutions can be found for working and protecting routes so as to restore a higher number of connections, through with the central processing of global information that is obtained at non-negligible signalling costs from the network [66]. On the other hand, algorithms devised and evaluated on the assumption that all nodes are algorithmically identical make clearer their strength of spreading the communication and processing over the network, efficient resource allocation, and also handling resource failures more easily [67],[68]. The Multi Commodity Multiple Flow (MCMF) approach has also been used for designing a distributed restoration algorithm [69].

Studies on self-healing optical networks are centered around three issues: the use of centralized computation versus distributed computation, the use of link rerouting versus path or end-to-end rerouting, and the use of precomputed versus dynamically computed routes [70].

Traffic engineering requirements in multiclass service environments are serious concerns of traffic engineering for IP over WDM integration. Multi Protocol Label Switching (MPLS) has gained wide acceptance in this context [71]. The internet currently provides services on a best-effort basis. The reliability and quality of the delivered service (QoS) can not be guaranteed. QoS and reliability of services must be engineered and guaranteed for next generation networks. In the present structure, application servers are at the edges of the network and services do not fit into a unified architecture. Heterogeneous networks, each employing different transport and control technologies, need to be transformed into a unified, multiservice, data-centric network offering services at different qualities and costs [72].

MPLS can be used in a manner very similar to a synchronous optical network (SONET), where no signalling is necessary to perform the protection switching of the label-switched path (LSP), using predetermined routes. In virtual-circuit-based networks, protection may be provided by both SONET and routing protocols within the connection-oriented architecture [73].

MPLS provides a method to set up explicit paths and forward traffic on them, but it does not address the issue of how to find paths with constraints. To handle this problem, the Internet Engineering Task Force (IETF) has been working on extending the commonly used Interior gateway protocols (IGPs), Open Shortest Path First (OSPF) and Intermediate System–Intermediate System (IS-IS) to carry additional information about links which includes, maximum link bandwidth, maximum reservable bandwidth, current bandwidth reservation, a default traffic engineering metric, and the resource class or color of the link. For instance, links of certain colors may be avoided for reasons of security [74]. Lightpath arrival and node/link failure statistics can be used to predict the reconfiguration probability and find the optimal route using these probability values [68].

Multi Protocol Lambda Switching (MPLambdaS), where optical channels are viewed as analogous to labels in MPLS, has been proposed within the IETF as an extension of MPLS for optical networks [75]. To state the MPLS versus MPLambdaS disagreement, it is not clear whether the control entity within IP layer routers will be topologically aware of what pattern of optical cross connect (OXC) traversals constitutes the lightpath, or whether the optical layer will set these up autonomously and tell the IP layer where the endpoints are without saying which sequence of OXCs constitute the lightpath. The second alternative seems likely to prevail [76].

MPLS protocols need to be extended to manage optical networks. For example, MPLS LSPs are

unidirectional, while connections in optical networks are generally bidirectional. These protocols must also be extended to handle all-optical networks without wavelength conversion, in which connections must be established on a common wavelength on every link along their chosen routes [75].

A standardized signalling system must be designed to provide optical networks with a common language and mechanism to convey connection-related information like client and connection identifiers, source, destination addresses and ports, security objects, framing type and use, bandwidth, directionality (whether the connection is unidirectional, bidirectional, or multicast), priority and preemptability, protection and restoration, relationships between lightpaths, and specified routing [75].

IP over WDM has usually meant IP packets mapped into synchronous optical network/synchronous digital hierarchy (SONET/SDH) coupled with SONET/SDH based point to point dense wavelength division multiplexing (DWDM) systems [77]. IP packets are statistically multiplexed over connections [78]. Development of practical all-optical crossconnects (OXC's) and all-optical add-drop multiplexers (OADMs) make it possible to evolve from simple point-to-point WDM links to real all-optical networks [76].

Considering the present infrastructure, SONET/SDH self-healing rings enable service level recovery within tens of milliseconds following network failures, but data service providers do not have the network infrastructure support to provide customer specific differentiated service guarantees and corresponding service level agreements [77].

Standards and products must be developed to eliminate one or more of the intermediate layers and run IP over WDM, increasing bandwidth. Integrating higher layer topology control decisions using optical layer RWA schemes is largely a manual process today [79]. Routing stability, coordination between IP and WDM layer protection are still open problems [80]. IP routers will need enhancements to enable them to interface directly with DWDM devices and to provide a suitable substitute for many of the management and restoration capabilities offered by SONET today [81]. Consequently, there is need for further work on how to design, simulate, and separate various tasks like protection/restoration among various layers [80].

It is necessary to develop faster and more robust protection and restoration mechanisms for IP networks with special consideration of applications sensitive to data loss and packet delay as VoIP [82].

An optical layer may handle some key functions which currently reside in different network layers like channel routing, channel monitoring, fault detection and recovery capabilities [79]. It is hard for higher layer (i.e. IP) schemes to face unpredictable physical to logic fault multiplication, and there is a lack of awareness of the exact capacity of transport spans available for restoration. So there is interest in transmission level (SONET/WDM) restoration, especially in cases of fiber optic cable cuts [70].

A possible approach is to restore fiber optic cable cuts in the SONET or WDM layer (where restoration directly replaces the prefailure capacity at the transmission carrier signal level). Single logical link or node failures in higher layers have to be protected by a suitable scheme in the higher layer itself (OSPF in IP routers). Different techniques are being employed for restoration after failures. (i.e. SONET self-healing rings) [70].

Generally, service and restoration path problems are solved jointly. Thus more resource sharing between service and restoration paths will be possible [30]. Performance of most algorithms to find optimum service and restoration paths depend weakly on the initial network configuration, and the order in which node pairs are considered within an iteration [83].

Two main optical protection schemes have been widely implemented [80]:

- **Optical Multiplex Section(OMS) Level Fiber Protection switching:**

Every working fiber is backed up by another disjointed protection fiber path in the ring (i.e. Automatic Protection Switching). Although this is fast, it causes low resource utilisation.

- **Optical Channel Level (Wavelength Level) Protection:**

This can be handled in three ways:

1. Link protection: Reroutes the traffic between the end nodes of the failed link. Link protection supplies the fastest failure detection and tries to recover traffic locally at the expense of efficiency (more hops, more bandwidth, more end-to-end delay).
2. Path Protection: Reroutes the broken traffic between the two ends of the affected path. It takes full advantage of the spare capacity all over the network with lower spare capacity requirement but longer time to detect failure, propagate error notification to source node and set up the alternate path.
3. Disjoint-link path protection: “Link-disjoint” constraint is added to the path selection. Once the path failure is discovered, traffic is restored immediately. As there is no need to know the exact location of the failure, it is capable of protecting against multiple simultaneous failures on the working path.

Optical layer protection and restoration can not handle all types of faults in the network. Failure of a laser in an IP router or a synchronous optical network add-drop multiplexer (SONET ADM) attached to the optical network must be handled by the IP or SONET layer, respectively. The optical layer can not provide different levels of protection to different parts of the traffic being carried on a lightpath (part of the traffic may be high-priority, the other lower-priority) since it protects traffic in units of lightpaths. This function must be performed by a higher layer that handles traffic at this finer granularity. So as not to produce race conditions, the overall network must be handled carefully while the optical layer and client layer both try to protect traffic against a failure simultaneously [66].

Consequently, protection can take place at a number of layers in the network: WDM, SONET, MPLS, and so on. It is typically better to let the lowest layers try to recover first since they can usually recover a larger number of higher-layer connections in a single operation; on the other hand, recovery at higher layers can be more robust. Since multiple layers of protection need to be coordinated, advertising the layer along with the protection information within a link state protocol is highly desirable [76].

Handling multiple failure recovery scenarios [71], optimizing algorithms for networks with layered topologies such as ring of rings and mesh of rings [30], packet and hybrid switching schemes [79], and security requirements [84] still require further investigation. Considering hybrid switching methods which combine optical circuit switching with fast opto-electronic or even optical packet switching, it is challenging to process header bits optically [79].

Considering other recent trends in WDM research, optical packet and optical burst switching techniques are at an experimental stage. Optical packet switches suffer from the immaturity of optical buffering technology. Furthermore, it is not clear how such switches can be deployed to carry IP traffic. Ideal packet size and required memory in an optical switch must be determined. Optical burst switching can be more promising if designed without requiring optical buffering. The performance of various burst switching schemes must be studied considering IP traffic [85].

The lightpath concept can be extended to point-to-multipoint, i.e. multicast concept, which is called a “light tree”. Light trees placed on an optical WDM backbone network can improve the performance of

unicast, multi-cast, and broadcast traffic but multicast-capable optical switches and extra power budgets to overcome the effect of power losses due to signal splitting are needed [86].

Although the role of wavelength converters in optical transport network restoration has been studied extensively, it still requires further elaboration. Due to the joint assignment of routes and wavelengths, the design problem for wavelength selective networks is much more difficult, and the solutions given by heuristic algorithms are still far from optimal [30].

Considering IP-WDM integration again, either WDM interface must be designed to work with today's IP (IPv4, IPv6 etc.) or an improved version of IP must be developed that can exploit the properties of WDM [86].

5. Conclusion

Optical networking remains the most important transmission medium and has enabled the explosive growth of communications networking for many years. Optical transmission properties (large bandwidth, low error rate, low attenuation), and transport networking functions supplied by SONET/SDH delivered major improvements in capacity, reliability, and efficiency. The introduction of WDM has also played an important role in satisfying the growing bandwidth demand over the last few years. WDM is often a more cost-effective way to expand capacity than other alternatives, such as installing more parallel fibers or replacing current TDM systems with higher-rate systems. Therefore, point-to-point WDM links have become widespread in recent years. WDM represents the first step towards all-optical networking. However, such networks have not replaced underlying TDM systems such as SONET/SDH, instead they provide point-to-point links, leaving most of the networking functionality to the upper layers.

If traffic demand continues to grow at the same rate, and WDM deployment continues, optical channels will increasingly become the fundamental transmission medium. In the near future, more and more wavelength channels will be multiplexed in a single fiber, and channel rates will increase up to peak electronic rates. Therefore, the electronic switches at fiber ends are expected to become increasingly complex and costly. This will favor the replacement of electronic switches by optical switches. In future networks, switching will be done at the optical layer by using wavelength routing devices, and networks will supply end-to-end high capacity optical pipes between network users. This will enable optical transport networking based on wavelength routing. That is, in next generation networks, transport-networking functions, which are presently handled by upper layers, will be handled at the optical layer. Therefore, optical transport networking based on wavelength routing represents the next step in the evolution of transport networking.

On the other hand, due to their high cost, all-optical local and metropolitan area networks based on broadcast and select networks are currently far from competing with other technologies such as ATM, and gigabit ethernet. In the near future, only a few applications that strongly need large capacity (i.e., supercomputer visualization) will be appropriate for broadcast and select networks. However, as new applications and/or services that require very large bandwidths emerge, all-optical networking in LANs and MANs will be an important choice.

As all-optical networks in local and metropolitan areas become widespread, the interconnection of these networks in an all-optical way will be an important issue. Today, there are some hierarchical approaches proposed for this purpose. Most of these organizations are suitable for circuit switched traffic. However, sdata traffic will become a dominant client of future communication networks, and packet switching will continue to be very important. Therefore, packet switching technologies will play an important role in proliferation of

all-optical networks. To support packet switched traffic between all-optical local area networks, wavelength routing packet switches that are interconnected by virtual topologies over optical transport networks can be employed. Therefore, today's protocol stacks of the form applications/TCP/IP/ATM/SONET/optical (or applications/ATM/SONET/optical) may evolve to applications/IP/optical (or applications/ATM/optical) or even applications/optical. The rate of increase in traffic and advances in optical networking will determine the speed of this evolution.

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