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10 Multiwavelength Optical Networks (WDM)

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CONTENTS

This chapter discusses the evolution of high-capacity wavelength division multiplexed (WDM) networks or multiwavelength optical networks from point-to-point configurations to more advanced flexible and survivable network architectures. It discusses architectures that enable a flexible and survivable WDM optical layer for a data-centric network. In particular, it proposes three architectures: WDM optical cross-connect mesh (W-Mesh), WDM unidirectional path switched ring (W-UPSR) and WDM bidirectional line switched ring (W-BLSR). These architectures provide a cost-effective evolution to a high capacity data-centric environment.

10.1 INTRODUCTION

Traffic growth in the Internet and other new data communications have resulted in new business opportunities and challenges for telecommunications network operators. The number of Internet hosts has grown hundred-fold from 1990 to 1998, and the resulting demand is straining the capacity of the telecommunications network infrastructure. In the past, telecommunications network design and economics have been determined by voice traffic considerations. It is now apparent that the dominant traffic in the network will be data. This results in a fundamental change in principles underlying network architecture choice and technology. It is envisioned that the wavelength division multiplexed (WDM) optical networking layer will form the core of this data-centric network architecture and provide the network operator with functionality similar to that which SONET (synchronous optical network) TDM (time division multiplexing) has provided in a voice-centric environment. SONET TDM terminals support several rates of OC-3 (corresponds to 155 Mbps), OC-12 (corresponds to 622 Mbps), OC-48 (corresponds to 2.5 Gbps), OC-192 (corresponds to 10 Gbps), etc.

10.2 POINT-TO-POINT WDM NETWORKS

WDM optical systems combine several optical wavelengths (e.g., separated by 100 GHz in the 1550 nm band of the spectrum) in a single fiber. These multiplexed wavelengths are then amplified by erbium-doped fiber amplifiers (EDFAs) that boost signals to overcome losses in transmission (see Sternard Bala,[8] Bala,[1] and Brackett[3]). As shown in Figure 10.1, these point-to-point WDM systems are mostly deployed in open architectures with 1.3 μm standard short-reach SONET interfaces. These interfaces interconnect directly to equipment like SONET TDM equipment, or Internet Protocol (IP) routers and asynchronous transfer mode (ATM) switches that support the standard SONET interfaces. The part of WDM systems that converts a 1.3 μm signal into an ITU wavelength signal in the 1550 nm band is called a transponder. Also, the WDM multiplexers and demultiplexers along with EDFAs in a typical long-haul network configuration are shown in Figure 10.1.

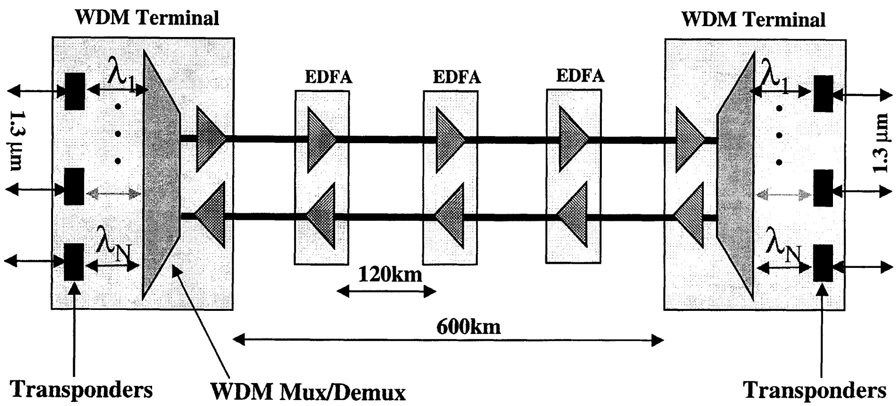


Figure 10.1 Open WDM Architecture

WDM is a proven method of increasing bandwidth by a factor of 30-50% of the cost of alternate methods. These cost advantages are particularly significant in cases where new fiber builds are avoided by using WDM equipment. In cases where a route between central offices runs out of capacity because of fiber exhaust, it can cost up to a $100,000/mile to lay new fiber facilities. In this case, the ability to increase the capacity of existing fibers by multiplexing several wavelengths adds tremendous economic value. Several long-distance network and local-exchange carriers have less than 50% fiber available in their cables. In addition, the long haul carriers have a small number of fibers per cable. This exacerbates the fiber exhaust problem and has brought about a mass deployment of WDM into the network.

The capacity of point-to-point WDM systems is increasing rapidly. The first systems were deployed with 8 wavelength channels. The number of wavelengths deployed in the network has increased to 40 wavelengths recently. Vendors have already announced the availability of up to 128 wavelengths per fiber. The total span of these systems varies from tens of km (local) to 1000 km (long haul) with optical amplifiers at intermediate locations for boosting the signal level. Several network operators have already deployed these systems and are looking to increase the number of wavelengths per fiber to even higher counts. The International Telecommunications Union has specified a 100 GHz spacing for the wavelengths. However, several equipment providers have announced products based on 50 GHz spacing and are considering 25 GHz spacings for adjacent channels. At the same time, the EDFA band has been flattened and increased by using dual-stage amplifiers with intermediate stage filters. New advancements in optical amplifiers[8] and lasers suggest there is still much room for growth in the number of wavelengths carried on a single fiber.

Now consider advanced network architectures that introduce configurability, flexibility, and survivability into the WDM optical layer. Figure 10.2 shows the overall network architecture vision for WDM optical networks. Traditional TDM networks demultiplex all the traffic down to sub-rates (e.g., DS3 at 45 Mbps) and perform capacity routing and assignment at the lower rates. This strategy makes sense in a voice-centric network where the fundamental unit is the 64 Kbps channel. In a data-centric network, equipment such as IP routers and ATM switches support optical interfaces (e.g., OC-Nc concatenated SONET interfaces). This requires that the traffic not be demultiplexed to lower rates but be routed and managed at the higher optical concatenated rates. Any demultiplexing operation is both unnecessary and costly. The optical layer allows such pass-through traffic at a node to traverse the node optically without any demultiplexing down to the lower sub-rates. However, the optical layer now has to provide the flexibility and survivability that the network operators are accustomed to obtaining from the SONET layer.

Consequently, the WDM optical networking layer must have an open architecture with interfaces that enable it to carry signals originating from equipment such as IP routers, ATM switches, and SONET terminals. This implies that the WDM layer must be configurable, survivable, and manageable. This chapter discusses and compares several architectures that will enable a flexible optical networking layer by providing survivability and dynamic wavelength provisioning while minimizing manual intervention.[1] These architectures are enabled by two key network elements: the reconfigurable wavelength-add/drop multiplexer (WADM)[7] and the optical cross-connect.[1]

10.3 WDM OPTICAL CROSS-CONNECT MESH (W-MESH)

The large deployment of point-to-point systems has resulted in numerous wavelengths terminating at the central offices. This in turn has resulted in a strong need to manage these wavelengths at the optical level without sub-rate demultiplexing of the individual connections. Figure 10.2 shows a central office that has several WDM systems deployed in a mesh network architecture. Traffic patterns in data networks

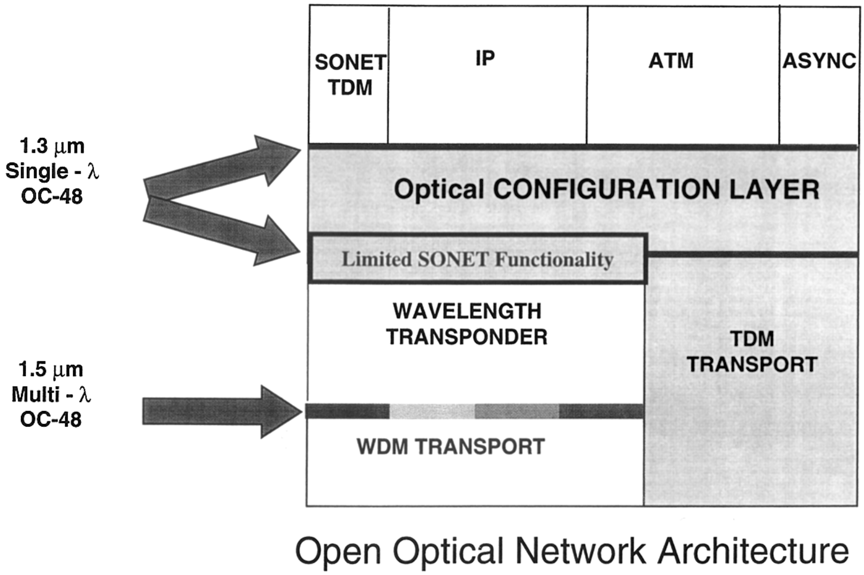


Figure 10.2 WDM Optical Networking Architectural Vision

are expected to be more arbitrarily mesh-like in their behavior. This is accentuated by the emergence of distributed applications on the web. As a result, mesh architectures for WDM networks need careful consideration.

Figure 10.3 shows a traditional digital crossconnect system (DCS) that has been optimized for telephony applications deployed in support of the WDM mesh network. Each incoming signal (e.g., 2.5 Gbps optical OC-48 SONET) at the DCS is demultiplexed down to smaller tributaries (e.g., STS-1 or 50 Mbps, VT1.5 or 1.5 Mbps) which are switched individually to output ports. The output ports re-multiplex the signals back for transmission (e.g., 2.5 Gbps optical OC-48 SONET). Thus, the traditional DCS switching allows for grooming and capacity allocation at lower rates. However, this lower rate processing becomes unnecessary (and very uneconomical) in an environment in which large volumes of traffic (e.g., several optical signals at OC48 rate or 2.5 Gbps from WDM transport systems) pass through a node (e.g., > 25%) without requiring any lower-rate grooming. This situation is faced by carriers that have deployed large numbers of WDM point-to-point systems in mesh.

Another problem with current DCS-based mesh networks is that sub-rate switching is an impediment to fast restoration from catastrophic events such as link and node failures. The restoration algorithms must restore at the sub-rate level. This situation results in slower restoration times on the order of seconds or minutes in these mesh networks. There is also a limit on the total number of sub-rate connections that can be restored in such a network.

Also, several equipment providers have announced ATM switches and IP routers with OC-Nc concatenated SONET interfaces where N = 3 to 192. The

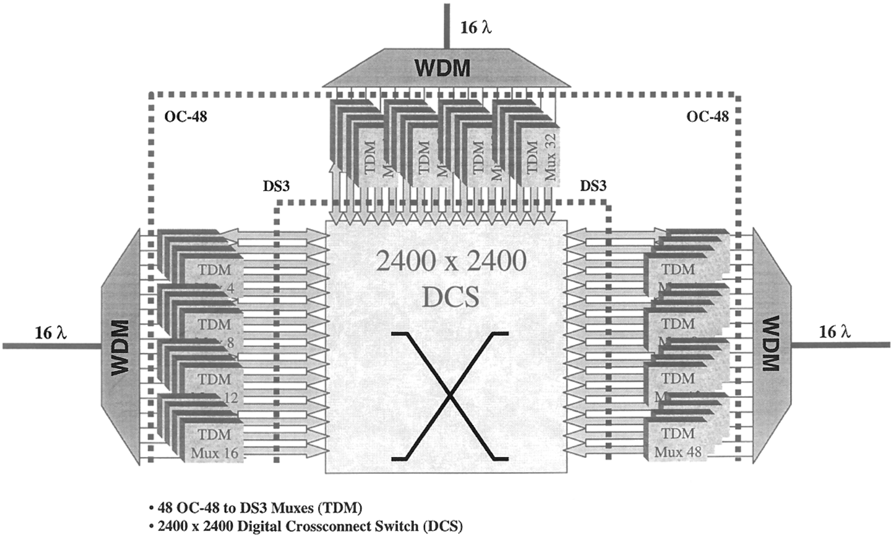


Figure 10.3 Traditional Digital Crossconnect System (DCS) in a WDM Point-to-Point Network

interfaces are specified as concatenated, which means that the entire bit stream is required to stay together from source to destination. In this case, demultiplexing the signal down to lower rates is unnecessary and uneconomical. However, these signals are unnecessarily demultiplexed and remultiplexed to lower rates, such as 1.5 Mbps, as they traverse the DCS. Since access to these sub-rate tributaries are not required in these data networks, it is expensive to take these OC-Nc signals apart and put them back together.

Figure 10.4 shows a WDM mesh network node that uses WDM transport systems in conjuction with OCS to provide dynamic wavelength assignment and restoration at the optical layer in an opaque network architecture.[2] The opaque architecture clearly separates switching from transport and eliminates any cascaded impairments that accumulate during transmission by providing signal regeneration between the WDM transport systems and the OCS. Furthermore, it enables wavelength interchange functionality between WDM transport systems by using the 1.3 μm interface as a common intermediate frequency between two WDM systems. In this fashion, it enables multivendor interoperability and allows different wavelength sets from different vendors to be interconnected by bringing them all to a common denominator, the 1.3 μm standard interface. The OCS will be deployed to operate in conjunction with existing WDM point-to-point systems providing interconnection and interoperability between them. In such a scenario, the point-to-point systems and the OCS might be provided by independent suppliers with interoperability achieved using a standard open interface, e.g., the 1.3 μm short reach SONET interface.

In this architecture, optical signals pass through the OCS without demultiplexing the signal down to the tributary sub-rate level. Besides significant cost and space

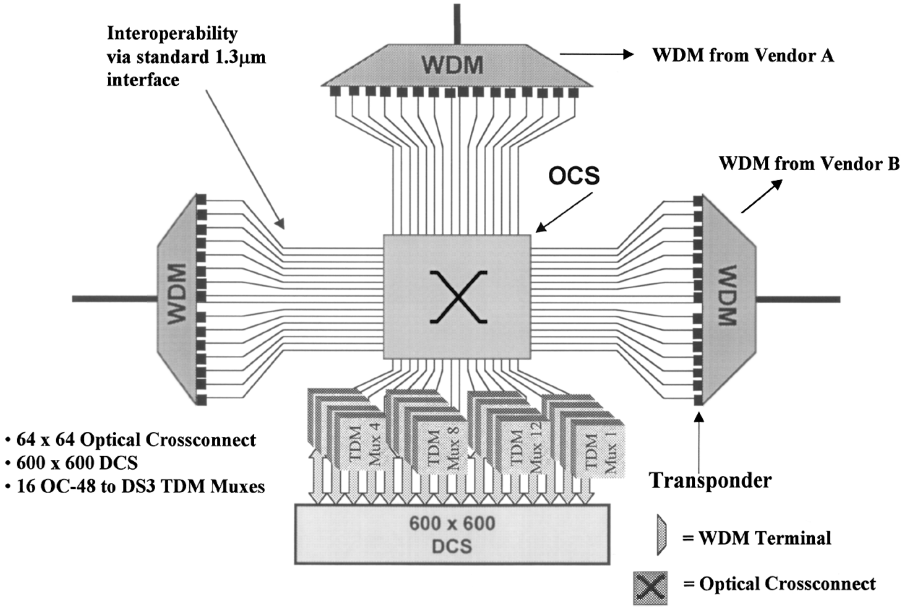


Figure 10.4 Optical Crossconnect (OCS) in a WDM Mesh Architecture

savings (at a factor of 5-10 over a traditional DCS solution), the OCS allows a direct interface to IP routers and ATM switches. Support for OC-Nc concatenated interfaces comes about naturally using the OCS. Furthermore, since the restoration is done at the optical layer (not at the lower rate tributaries), restoration times are expected to approach that of SONET rings (50 msecs).

Figure 10.3 shows three WDM terminals supporting 16 wavelengths each at OC-48 rates (2.5 Gbps). Each of these OC-48 signals is demultiplexed to 48 individual DS3 signals (approximately 50 Mbps) using a SONET terminal. A total of 48 TDM SONET terminals are required (one/wavelength). These DS3s are then switched through a DCS that has a maximum size of 2400 DS3 ports. Figure 10.4 shows the same scenario using one 64-port OCS and a smaller DCS with 600 ports resulting in a significant savings over the traditional DCS, assuming that 75% of the traffic passes through the node without requiring demultiplexing.

10.4 WAVELENGTH BIDIRECTIONAL LINE-SWITCHED RINGS (W-BLSR)

A 2-fiber W-BLSR architecture comprises two counter-rotating rings as shown in Figure 10.5. The figure shows a connection between two nodes on a wavelength channel. In this architecture only the working path is set up without dedicating the protection. The protection is shared among all the working paths on the ring.

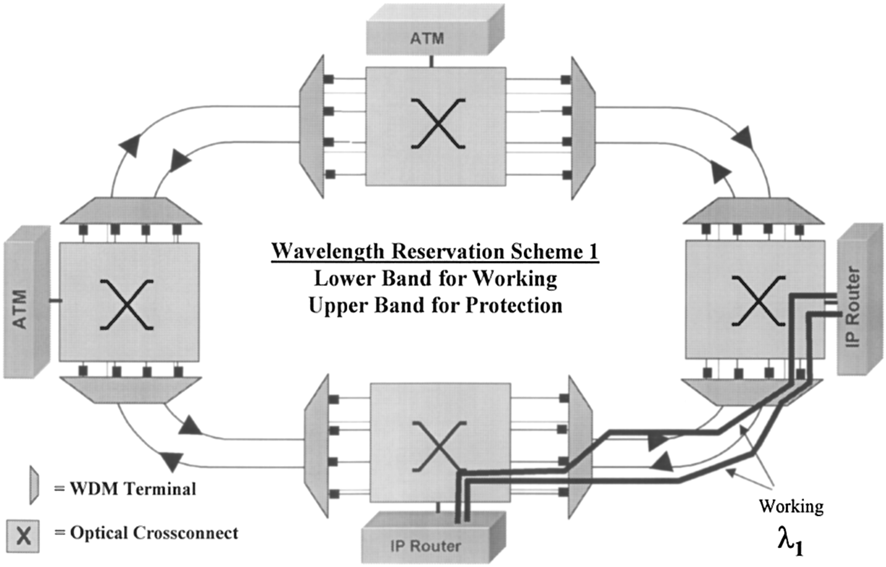


Figure 10.5 2-fiber WDM Bidirectional Line Switched Ring (2F W-BLSR) with λ Reservation Scheme 1

Automatic protection switching (APS) against failures is achieved by reserving half the wavelengths on each fiber for working traffic and the other half for protection on each fiber. Two wavelength reservation schemes are possible:

1. The lower band of wavelengths is used for working traffic in each fiber and the upper band of wavelengths is used for protection traffic in both directions on the two counter-rotating fibers.
2. In one direction the upper band is used for working traffic and the lower band for protection. In the opposite direction the lower band is used for working traffic and the upper band is used for protection traffic.

Both cases require configurable WADM. However, in the first case above, when there is a fiber cut a wavelength interchange operation is required at the two ends of the cut in order to move working traffic in one direction onto protection wavelengths in the opposite direction. On the other hand, case 2 above does not require the use of wavelength interchange because of the unique wavelength reservation strategy employed.

Figure 10.5 shows a 2-fiber W-BLSR ring with a bidirectional connection between two nodes on wavelength λ_1. In this case, the lower band of wavelengths (λ_1 through $\lambda_{w/2}$) are reserved for working and the upper band of wavelengths ($\lambda_{w/2}$ through λ_w) are reserved for protection. Figure 10.6 shows the same ring with a link failure. The two nodes adjacent to the failure perform a wavelength interchange

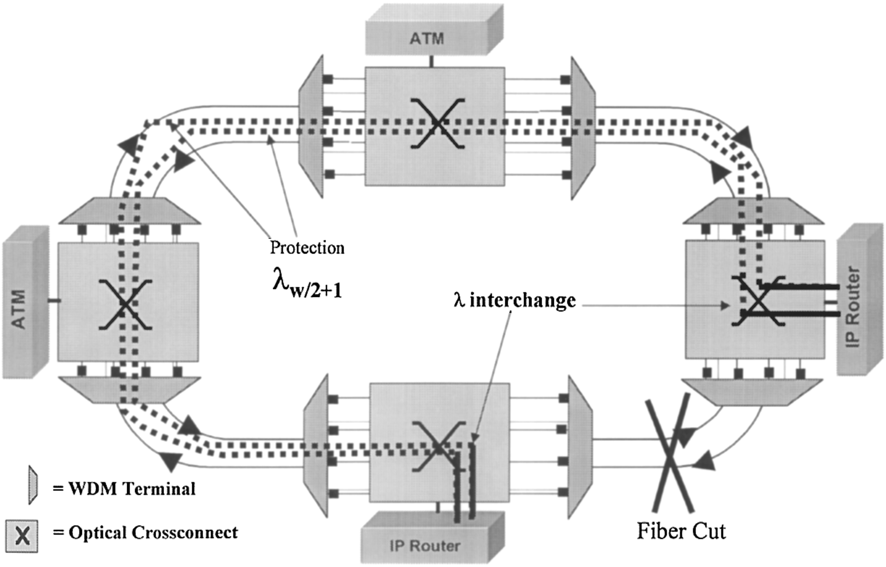


Figure 10.6 2-fiber W-BLSR with λ Reservation Scheme 1 (Fiber Cut)

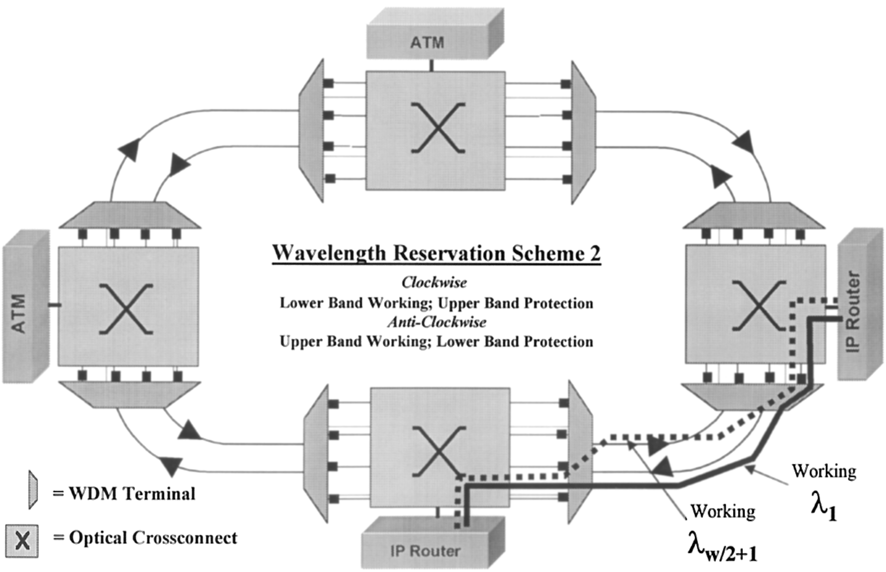


Figure 10.7 2-fiber WDM Bidirectional Line Switched Ring (2F W-BLSR) with λ Reservation Scheme 2

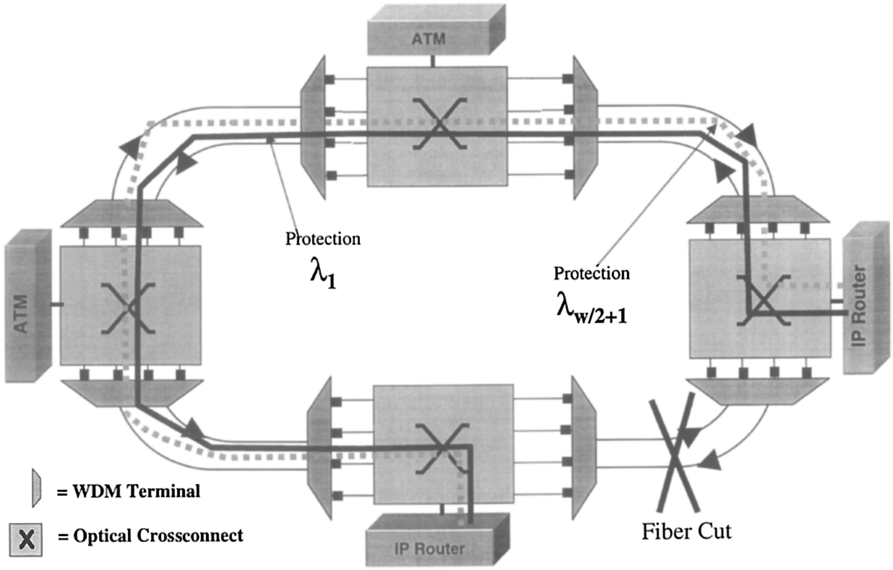


Figure 10.8 2-fiber W-BLSR with λ Reservation Scheme 2 (Fiber Cut)

operation to move the signal on λ_1 to wavelength $\lambda_{w/2+1}$ in the opposite direction for protection. In the near term, the only practical way to perform the required wavelength interchange is via optoelectronic conversions. However, in core networks, these optoelectronic conversions might be needed anyway to clean up the transmission impairments accumulated over long distances.

Figure 10.7 shows the 2-fiber W-BLSR ring with wavelength reservation scheme 2. This scheme results in the allocation of different wavelengths for the two directions of each bidirectional connection. Figure 10.8 shows the operation of the W-BLSR ring under a link failure condition. Note that in this case a wavelength interchange is not required during ring switching. Wavelength reservation scheme 1 is simpler to use from the point of view of network operations. It allows the assignment of the same wavelength to both directions of a two-way connection. Furthermore, this scheme reduces the amount of spare inventory by reducing the number of wavelengths that are assigned to connections.

Figure 10.9 shows a 4-fiber WDM bidirectional line switched ring (W-BLSR). This architecture is especially useful in long distance networks where span switching is important. Since the 4-fiber W-BLSR has dedicated fibers for working and protection, the protection fibers can be used to span-switch from a failure (e.g., transmitter). In span-switching, the failed traffic is moved to the protection fiber using the shortest path without needing to switch the traffic around the ring on the longer path. This also has the advantage of allowing testing, maintenance, and equipment upgrade on the protection fibers without service interruption.

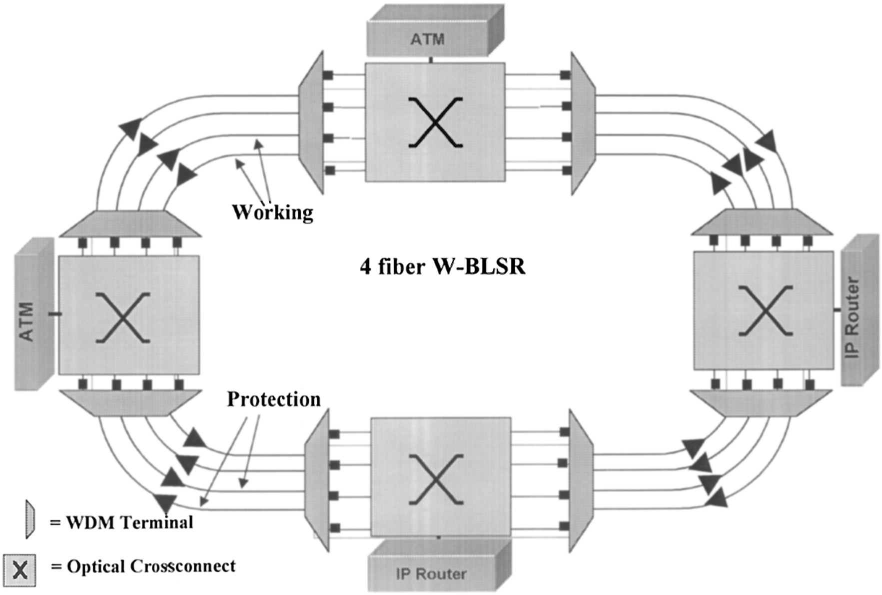


Figure 10.9 4-fiber WDM Bidirectional Line Switched Ring (4F W-BLSR)

10.5 WAVELENGTH UNIDIRECTIONAL PATH PROTECTION RING (W-UPSR)

The W-UPSR has one fiber dedicated for working and one for carrying protection traffic. Reconfigurable WADMs along the ring dynamically add and drop individual wavelengths from the working and protection fibers. As shown in Figure 10.10, in the W-UPSR, a wavelength path (e.g., an OC-48 signal on a wavelength) is bridged at the transmit end to create a working path and a dedicated protection path which are sent along opposite directions on the ring. Compare this architecture to the W-BLSR schemes discussed earlier that used shared, as opposed to dedicated, protection. The receiving end monitors both the working and the protection signals continuously. In case of a fiber cut, each receiving end switches independently to its protection path to provide Automatic Protection Switching (APS). Figure 10.11 shows the operation of the W-UPSR ring under a link failure condition. The WADM switches to the protection path and recovers from the link failure condition. The WADMs pass through traffic without demultiplexing the signals down to the lower speed tributary level. In this manner they offer significant cost and space savings compared to traditional TDM networks.

10.6 COMPARISON OF NETWORK ARCHITECTURES

We now compare the different network architectures from the standpoint of their capacity.

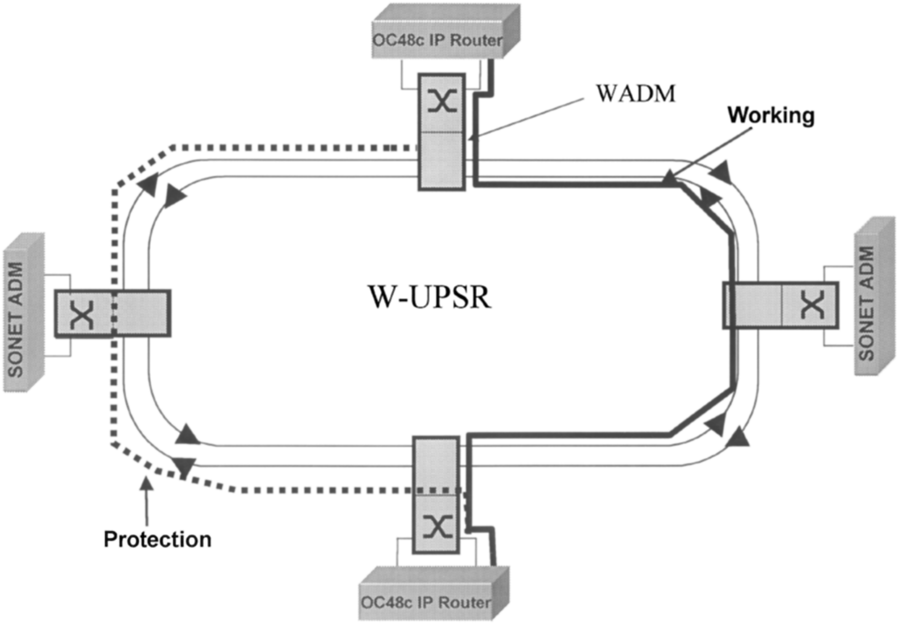


Figure 10.10 2-fiber WDM Unidirectional Path Switched Ring (W-UPSR)

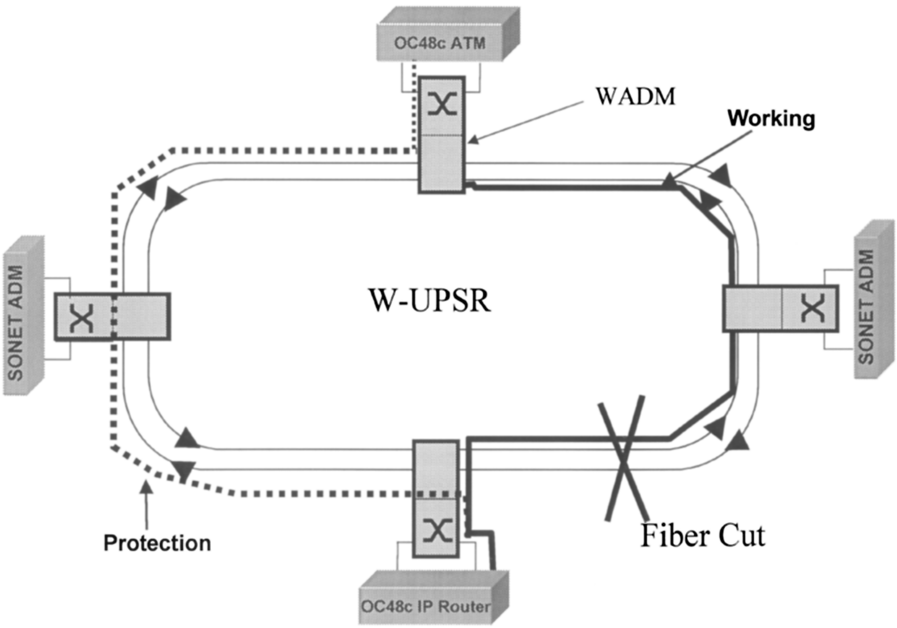


Figure 10.11 2-fiber W-UPSR (Fiber Cut)

Figure 10.12 shows a table comparing these three architectures with 10 network nodes each. The formulas used for the capacity calculations can be found in Stern and Bala.[8] It shows the number of wavelengths required in each architecture to support the required traffic pattern.

Architecture (10 nodes)	Number of Wavelengths	
	Hub Traffic *1 λ to each node from Hub*	**Mesh Traffic** *1 λ between every pair of nodes*
W-UPSR	9	45
2F W-BLSR	10	25
W-Mesh (degree 3)	3 + 2 (protection)	9 + 5 (protection)

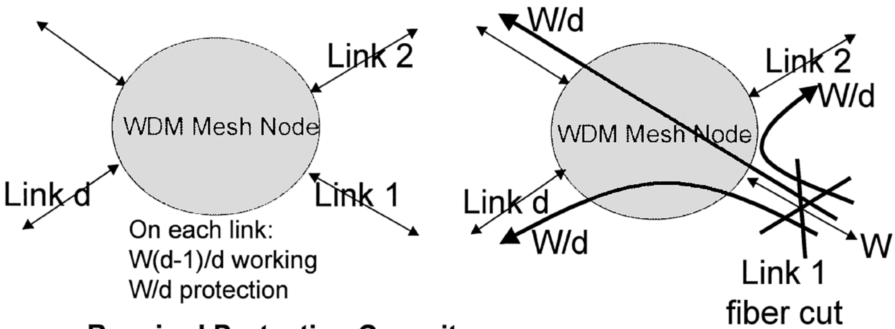
Figure 10.12 Comparison of Architectures: Network Capacity

Figures 10.13 and 10.14 compare the amount of protection capacity in a ring versus a mesh network. In a ring network the amount of redundant capacity reserved for protection is 50%. In a mesh network, the number of wavelengths/fiber reserved for protection is much less and is equal to W/d because in a mesh network there are (d-1) different routes along which a group of signals can be protected in case of a fiber cut.

In general, mesh networks offer significantly better network utilization by using a smaller number of wavelengths to support the same amount of traffic than do ring networks. On the other hand, mesh networks require more complex restoration algorithms for protection switching as compared to the UPSR case for ring networks. See Figure 10.15 for a comparison of the manageability of the architectures.

	Number of Wavelengths reserved for Protection
W-UPSR	W
2- fiber W-BLSR	W/2 per direction

Figure 10.13 Comparison of Architectures: Ring Protection Capacity



Required Protection Capacity:

W/d wavelengths per direction reserved on each link

e.g. For W = 12 and d = 3;

Working Capacity = 8 λ s, Protection Capacity = 4 λs

Figure 10.14 Comparison of Architectures: Mesh Protection Capacity

	Control & Management
W-UPSR	Simple - Tail End Switch
W-BLSR	Complex - Ring Coordination
W-Mesh	Complex - Network Coordination

Figure 10.15 Comparison of Architectures: Manageability and Network Protection

10.7 CONCLUSION

This chapter discussed the evolution of WDM networks from point-to-point systems to more complex architectures like rings and meshes. It introduced three WDM optical network architectures: W-Mesh, W-UPSR, and W-BLSR. The W-Mesh architecture has significantly better utilization than the W-BLSR and the W-UPSR rings; it uses the least number of wavelengths to route the same traffic. Also, the W-BLSR architecture results in more efficient utilization of network resources than does the W-UPSR. However, the W-UPSR is much simpler to manage for protection switching than are the W-BLSR and the W-Mesh networks.

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