



Introduction to DWDM Technology

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Preface

This *Introduction to DWDM Technology* is intended for readers who want to gain a basic understanding of dense wavelength division multiplexing (DWDM) technology and its role in metropolitan area networks (MANs). The contents are organized as follows:

Chapter	Title	Description
Chapter 1	Introducing DWDM	Differentiates the MAN from other segments of the global network; describes the driving forces behind DWDM; contrasts time division multiplexing (TDM) with wavelength division multiplexing (WDM); presents the advantages of DWDM in the MAN
Chapter 2	Fundamentals of DWDM Technology	Summarizes the evolution of fiber optic transmission and DWDM technology; briefly describes the main components; explains the operation of a DWDM system
Chapter 3	DWDM in Metropolitan Area Networks	Surveys the data link and network technologies used in the MAN; describes sample applications for DWDM; presents sample topologies and protection schemes; offers practical considerations for deploying DWDM

Additional Reading

Readers who are interested in more detailed information about optical networking will find that there is a wide selection of resources available, especially on SONET. The following publications are good, basic texts:

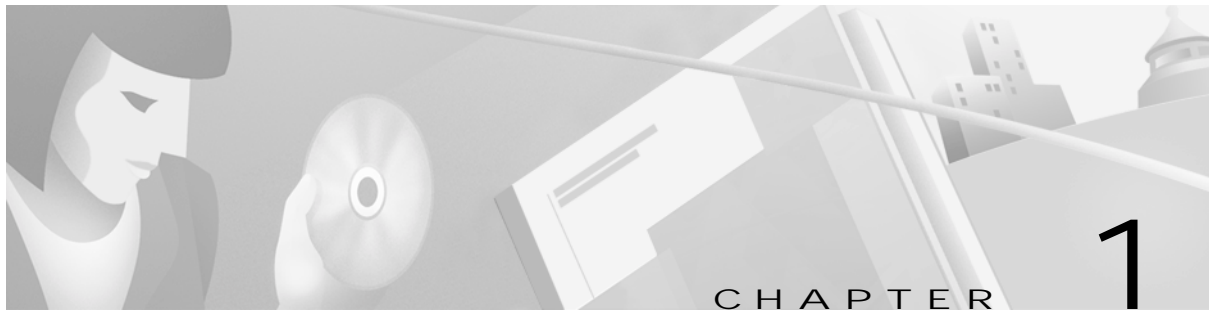
- Dutton, Harry J. R. *Understanding Optical Communications*. Research Triangle Park: IBM Corporation; 1998.
- Goff, David R. *Fiber Optic Reference Guide*, 2nd edition. Boston: Focal Press; 1999.
- Goralski, Walter J. *SONET*, 2nd edition. New York: McGraw-Hill; 2000.
- Kaminow, Ivan P., and Koch, Thomas L., eds. *Optical Fiber Telecommunications*. San Diego: Academic Press; 1997.

The following publication is a detailed text on DWDM, particularly from the standpoint of theory and optical components:

Kartalopoulos, Stamatios V. *Introduction to DWDM Technology: Data in a Rainbow*. New York: IEEE Press; 1999.

Although comprehensive texts specifically about DWDM are not yet plentiful, there is a variety of information in the form of tutorials, white papers, and so on, to be found on the World Wide Web.

For definitions of terms and acronyms used in this Introduction, refer to the *Glossary of Optical Networking Terms*.



Introducing DWDM

The following discussion provides some background on why dense wavelength division multiplexing (DWDM) is an important innovation in optical networks and what benefits it can provide. We begin with a high-level view of the segments of the global network and the economic forces driving the revolution in fiber optic networks. We then examine the differences between traditional time-division multiplexing (TDM) and wavelength division multiplexing (WDM). Finally, we explore the advantages of this new technology.

This chapter contains the following major sections:

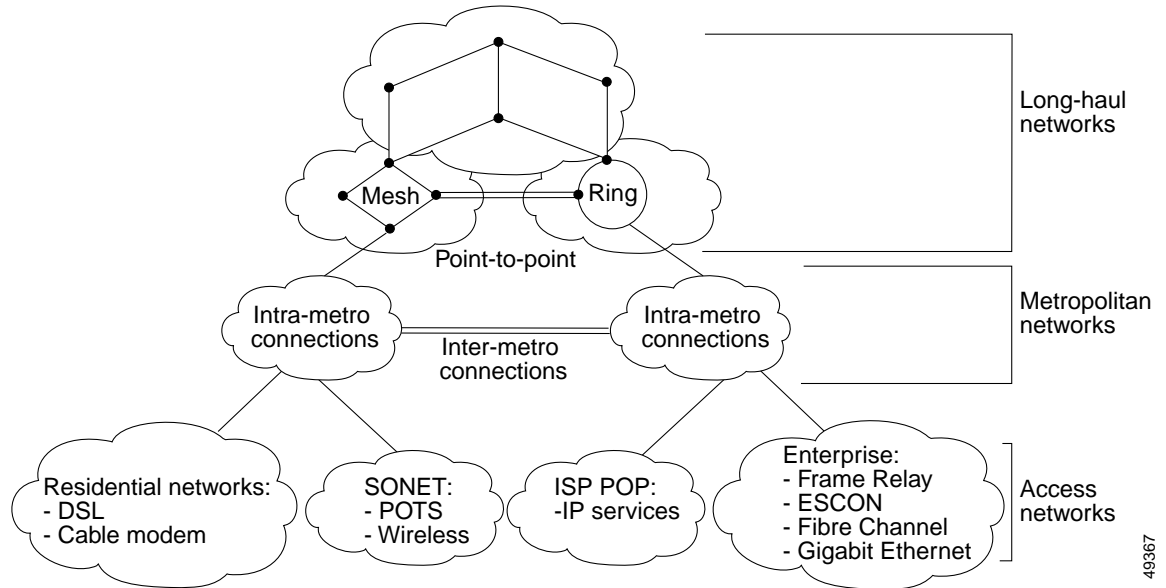
- Global Network Hierarchy, page 1-1
- Economic Forces, page 1-3
- Options for Increasing Carrier Bandwidth, page 1-5
- Additional Drivers in Metropolitan Area Networks, page 1-10
- Why DWDM?, page 1-12

Global Network Hierarchy

It is the nature of modern communications networks to be in a state of ongoing evolution. Factors such as new applications, changing patterns of usage, and redistribution of content make the definition of networks a work in progress. Nevertheless, we can broadly define the larger entities that make up the global network based on variables such as transport technology, distance, applications, and so on.

One way of describing the metropolitan area network (MAN) would be to say that it is neither the long-haul nor the access parts of the network, but the area that lies between those two (see Figure 1-1).

Figure 1-1 Global Network Hierarchy



Long-Haul Networks

Long-haul networks are at the core of the global network. Dominated by a small group of large transnational and global carriers, long-haul networks connect the MANs. Their application is transport, so their primary concern is capacity. In many cases these networks, which have traditionally been based on Synchronous Optical Network (SONET) or Synchronous Digital Hierarchy (SDH) technology, are experiencing fiber exhaust as a result of high bandwidth demand.

Access Networks

At the other end of the spectrum are the access networks. These networks are the closest to the end users, at the edge of the MAN. They are characterized by diverse protocols and infrastructures, and they span a broad spectrum of rates. Customers range from residential Internet users to large corporations and institutions. The predominance of IP traffic, with its inherently bursty, asymmetric, and unpredictable nature, presents many challenges, especially with new real-time applications. At the same time, these networks are required to continue to support legacy traffic and protocols, such as IBM's Enterprise System Connection (ESCON).

Metropolitan Area Networks

Between these two large and different networking domains lie the MANs. These networks channel traffic within the metropolitan domain (among businesses, offices, and metropolitan areas) and between large long-haul points of presence (POPs). The MANs have many of the same characteristics as the access networks, such as diverse networking protocols and channel speeds. Like access networks, MANs have been traditionally SONET/SDH based, using point-to-point or ring topologies with add/drop multiplexers (ADMs).

The MAN lies at a critical juncture. On the one hand, it must meet the needs created by the dynamics of the ever-increasing bandwidth available in long-haul transport networks. On the other hand, it must address the growing connectivity requirements and access technologies that are resulting in demand for high-speed, customized data services.

Metropolitan and Long-Haul Networks Compared

There is a natural tendency to regard the MAN as simply a scaled-down version of the long-haul network. It is true that networks serving the metropolitan area encompass shorter distances than in the long-haul transport networks. Upon closer examination, however, these differences are superficial compared to other factors. Network shape is more stable in long-haul, while topologies change frequently in the MAN. Many more types of services and traffic types must be supported in MANs, from traditional voice and leased line services to new applications, including data storage, distributed applications, and video. The long-haul, by contrast, is about big pipes.

Another important way in which metropolitan networks today differ from trunk-oriented long haul networks is that they encompass a collection of low bit-rate asynchronous and synchronous transmission equipment, short loops, small cross-sections, and a variety of users with varying bandwidth demands. These fundamental differences between the two types of networks have powerful implications for the requirements in the metropolitan domain. Protocol and speed transparency, scalability, and dynamic provisioning are at least as important as capacity, which rules in the long-haul market.

An Alternative View

The preceding breakdown of the global network represents a somewhat simplified view. In reality, the lines between the domains are not always so clear-cut. Long-haul and metropolitan networks are sometimes not clearly delineated; the same holds true for the access and metropolitan domains.

Furthermore, other views of the global network exist. One, for example, defines the access network as part of, rather than separate from, the MAN, while also including enterprise connectivity in the metropolitan domain. In this view, the metropolitan market breaks down as follows:

- Core—These are essentially scaled-down long-haul systems. They are considered the core of the MAN, because they interconnect carrier POPs and do not directly interface with end users.
- Metropolitan access—This is the segment between carrier POPs and access facilities, which could be equipment at customer premises or at an aggregation point.
- Enterprise—This is the part of the network dedicated to serving the needs of enterprises. Using owned or leased fiber (or leased fiber capacity), connectivity is provided between geographically disparate enterprise sites and for new applications, such as storage area networks (SANs).

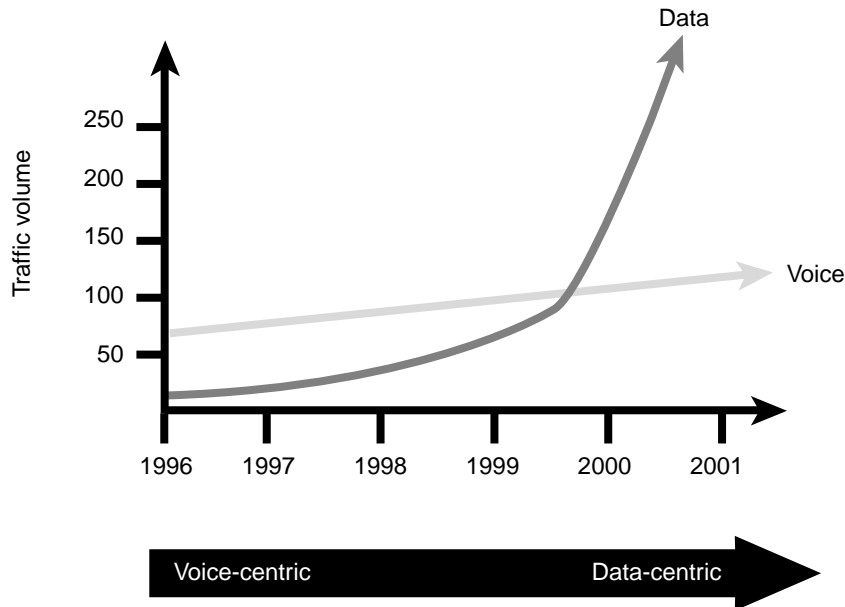
Economic Forces

As we enter the twenty-first century, it goes without saying that information services have permeated society and commerce. Information, while still a tool, has become a commodity in itself. Yet the universal acceptance and ubiquitous adoption of information technology systems has strained the backbones on which they were built. High demand—coupled with high usage rates, a deregulated telecommunications environment, and high availability requirements—is rapidly depleting the capacities of fibers that, when installed 10 years ago, were expected to suffice for the foreseeable future.

Bandwidth Demand

The explosion in demand for network bandwidth is largely due to the growth in data traffic, specifically Internet Protocol (IP). Leading service providers report bandwidths doubling on their backbones about every six to nine months. This is largely in response to the 300 percent growth per year in Internet traffic, while traditional voice traffic grows at a compound annual rate of only about 13 percent (see Figure 1-2).

Figure 1-2 Data Traffic Overtakes Voice Traffic



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At the same time that network traffic volume is increasing, the nature of the traffic itself is becoming more complex. Traffic carried on a backbone can originate as circuit based (TDM voice and fax), packet based (IP), or cell based (ATM and Frame Relay). In addition, there is an increasing proportion of delay sensitive data, such as voice over IP and streaming video.

In response to this explosive growth in bandwidth demand, along with the emergence of IP as the common foundation for all services, long-haul service providers are moving away from TDM based systems, which were optimized for voice but now prove to be costly and inefficient. Meanwhile, metropolitan networks are also experiencing the impact of growing congestion, as well as rapidly changing requirements that call for simpler and faster provisioning than is possible with older equipment and technologies. Of key importance in the metropolitan area is the growth in storage area networks (SANs), discussed in the “Storage Area Networks” section on page 3-5.

Competition and Reliability

While the demand for bandwidth is driven largely by new data applications, Internet usage, and the growth in wireless communications, two additional factors come into play: competition and network availability.

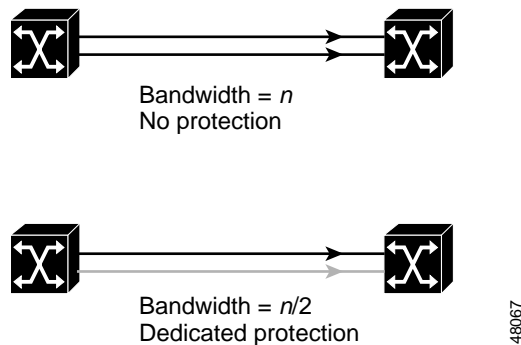
The telecommunication sector, long a beneficiary of government regulation, is now a highly competitive industry. Competition was first introduced into the U.S. long-distance market in 1984, and the 1996 Telecommunications Reform Act is now resulting in an increasingly broad array of new operators. These new carriers are striving to meet the new demand for additional services and capacity.

There are two main effects on the industry from competition:

- Enhanced services are created by newcomers trying to compete with incumbents. In the metropolitan market, for example, there are broadband wireless and DSL services to homes and small and medium-sized business, high-speed private line and VPN services to corporations, and transparent LAN services to enterprise network customers.
- New carriers coming onto the scene create new infrastructure so that they do not have to lease from existing operators. Using this strategy, they have more control over provisioning and reliability.

As telecommunications and data services have become more critical to business operations, service providers have been required to ensure that their networks are fault tolerant. To meet these requirements, providers have had to build backup routes, often using simple 1:1 redundancy in ring or point-to-point configurations. Achieving the required level of reliability, however, means reserving dedicated capacity for failover. This can double the need for bandwidth on an already strained infrastructure (see Figure 1-3).

Figure 1-3 Reserving Bandwidth Reduces Overall Capacity



Options for Increasing Carrier Bandwidth

Faced with the challenge of dramatically increasing capacity while constraining costs, carriers have two options: Install new fiber or increase the effective bandwidth of existing fiber.

Laying new fiber is the traditional means used by carriers to expand their networks. Deploying new fiber, however, is a costly proposition. It is estimated at about \$70,000 per mile, most of which is the cost of permits and construction rather than the fiber itself. Laying new fiber may make sense only when it is desirable to expand the embedded base.

Increasing the effective capacity of existing fiber can be accomplished in two ways:

- Increase the bit rate of existing systems.
- Increase the number of wavelengths on a fiber.

Increase the Bit Rate

Using TDM, data is now routinely transmitted at 2.5 Gbps (OC-48) and, increasingly, at 10 Gbps (OC-192); recent advances have resulted in speeds of 40 Gbps (OC-768). The electronic circuitry that makes this possible, however, is complex and costly, both to purchase and to maintain. In addition, there are significant technical issues that may restrict the applicability of this approach. Transmission at OC-192 over single-mode (SM) fiber, for example, is 16 times more affected by chromatic dispersion than the next lower aggregate speed, OC-48. The greater transmission power required by the higher bit rates also introduces nonlinear effects that can affect waveform quality. Finally, polarization mode dispersion, another effect that limits the distance a light pulse can travel without degradation, is also an issue. These characteristics of light in fiber are discussed further in the “Optical Fibers” section on page 2-6.

Increase the Number of Wavelengths

In this approach, many wavelengths are combined onto a single fiber. Using wavelength division multiplexing (WDM) technology several wavelengths, or light colors, can simultaneously multiplex signals of 2.5 to 40 Gbps each over a strand of fiber. Without having to lay new fiber, the effective capacity of existing fiber plant can routinely be increased by a factor of 16 or 32. Systems with 128 and 160 wavelengths are in operation today, with higher density on the horizon. The specific limits of this technology are not yet known.

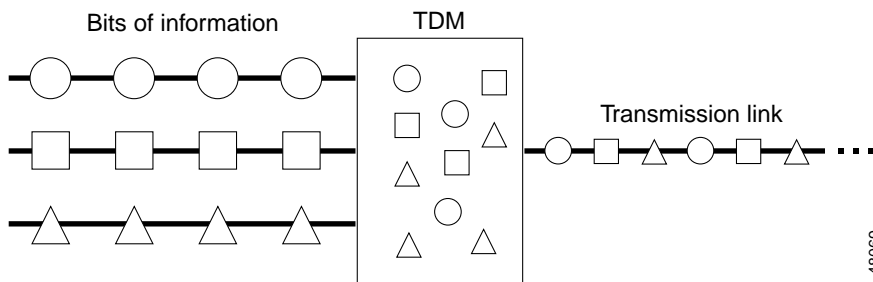
Time-Division Multiplexing

Time-division multiplexing (TDM) was invented as a way of maximizing the amount of voice traffic that could be carried over a medium. In the telephone network before multiplexing was invented, each telephone call required its own physical link. This proved to be an expensive and unscalable solution. Using multiplexing, more than one telephone call could be put on a single link.

TDM can be explained by an analogy to highway traffic. To transport all the traffic from four tributaries to another city, you can send all the traffic on one lane, providing the feeding tributaries are fairly serviced and the traffic is synchronized. So, if each of the four feeds puts a car onto the trunk highway every four seconds, then the trunk highway would get a car at the rate of one each second. As long as the speed of all the cars is synchronized, there would be no collision. At the destination the cars can be taken off the highway and fed to the local tributaries by the same synchronous mechanism, in reverse.

This is the principle used in synchronous TDM when sending bits over a link. TDM increases the capacity of the transmission link by slicing time into smaller intervals so that the bits from multiple input sources can be carried on the link, effectively increasing the number of bits transmitted per second (see Figure 1-4).

Figure 1-4 TDM Concept



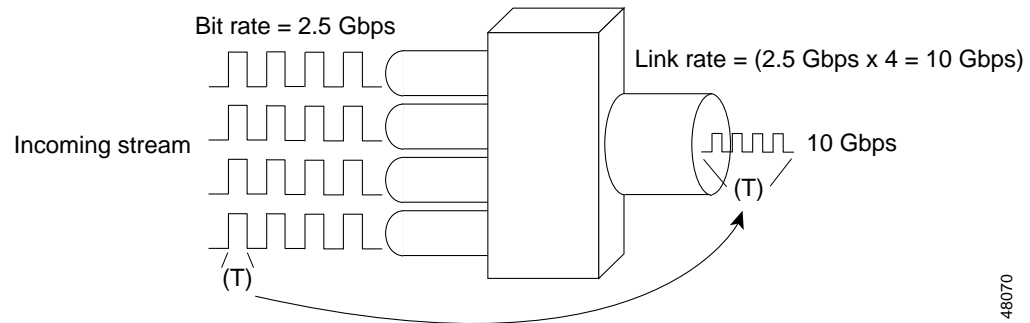
With TDM, input sources are serviced in round-robin fashion. Though fair, this method results in inefficiency, because each time slot is reserved even when there is no data to send. This problem is mitigated by the statistical multiplexing used in Asynchronous Transfer Mode (ATM). Although ATM offers better bandwidth utilization, there are practical limits to the speed that can be achieved due to the electronics required for segmentation and reassembly (SAR) of ATM cells that carry packet data.

SONET and TDM

The telecommunications industry adopted the Synchronous Optical Network (SONET) or Synchronous Digital Hierarchy (SDH) standard for optical transport of TDM data. SONET, used in North America, and SDH, used elsewhere, are two closely related standards that specify interface parameters, rates, framing formats, multiplexing methods, and management for synchronous TDM over fiber.

SONET/SDH takes n bit streams, multiplexes them, and optically modulates the signal, sending it out using a light emitting device over fiber with a bit rate equal to (incoming bit rate) $\times n$. Thus traffic arriving at the SONET multiplexer from four places at 2.5 Gbps will go out as a single stream at 4×2.5 Gbps, or 10 Gbps. This principle is illustrated in Figure 1-5, which shows an increase in the bit rate by a factor of four in time slot T .

Figure 1-5 SONET TDM



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The original unit used in multiplexing telephone calls is 64 kbps, which represents one phone call. Twenty-four (in North America) or thirty-two (outside North America) of these units are multiplexed using TDM into a higher bit-rate signal with an aggregate speed of 1.544 Mbps or 2.048 Mbps for transmission over T1 or E1 lines, respectively. The hierarchy for multiplexing telephone calls is shown in Table 1-1.

Table 1-1 Telco Multiplexing Hierarchy

Signal	Bit Rate	Voice Slots
DS0	64 kbps	1 DS0
DS1	1.544 Mbps	24 DS0s
DS2	6.312 Mbps	96 DS0s
DS3	44.736 Mbps	28 DS1s

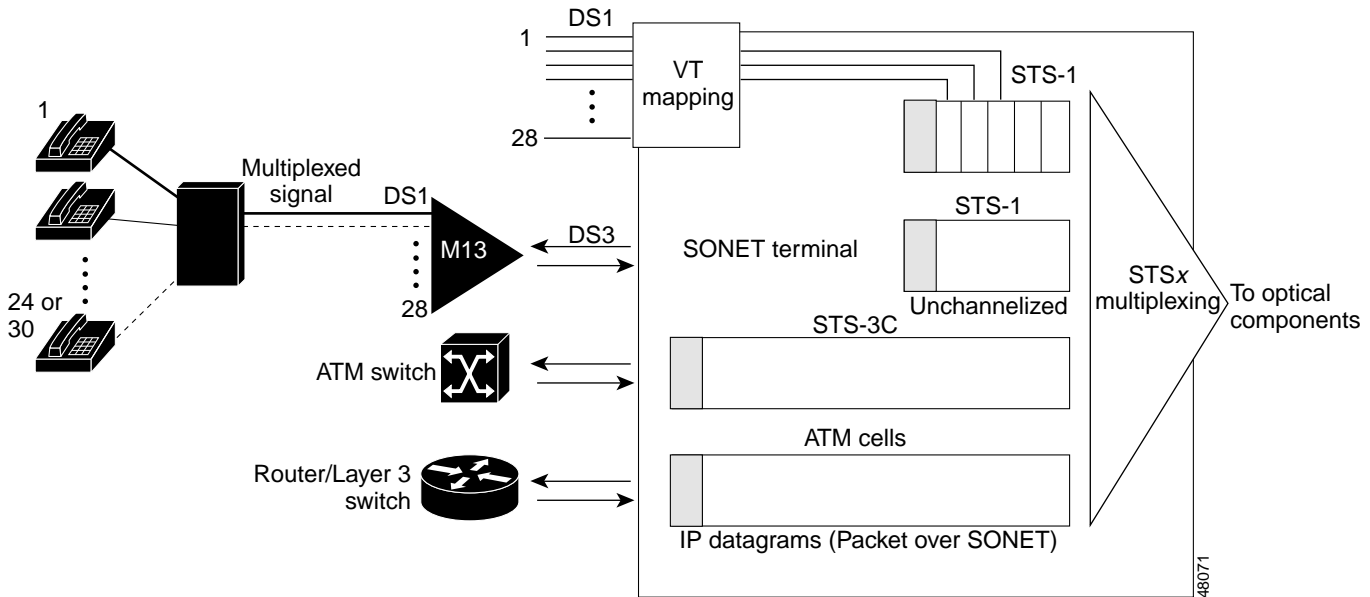
These are the basic building blocks used by SONET/SDH to multiplex into a standard hierarchy of speeds, from STS-1 at 51.85 Mbps to STS-192/STM-64 at 10 Gbps. Table 1-2 shows the relationship between the telco signal rates and the most commonly used levels of the SONET/SDH hierarchy (OC-768 is not yet common).

Table 1-2 SONET/SDH Multiplexing Hierarchy

Optical Carrier	SONET/SDH Signal	Bit Rate	Capacity
OC-1	STS-1	51.84 Mbps	28 DS1s or 1 DS3
OC-3	STS-3/STM-1	155.52 Mbps	84 DS1s or 3 DS3s
OC-12	STS-12/STM-4	622.08 Mbps	336 DS1s or 12 DS3s
OC-48	STS-48/STM-16	2488.32 Mbps	1344 DS1s or 48 DS3s
OC-192	STS-192/STM-64	9953.28 Mbps	5379 DS1s or 192 DS3s

Figure 1-6 depicts this multiplexing and aggregation hierarchy. Using a standard called virtual tributaries for mapping lower-speed channels into the STS-1 payload, the 28 DS1 signals can be mapped into the STS-1 payload, or they can be multiplexed to DS3 with an M13 multiplexer and fit directly into the STS-1. Note also that ATM and Layer 3 traffic, using packet over SONET (POS), can feed into the SONET terminal from switches equipped with SONET interfaces.

Figure 1-6 TDM and SONET Aggregation



SONET/SDH does have some drawbacks. As with any TDM, the notions of priority or congestion do not exist in SONET or SDH. Also, the multiplexing hierarchy is a rigid one. When more capacity is needed, a leap to the next multiple must be made, likely resulting in an outlay for more capacity than is initially needed. For example, the next incremental step from 10 Gbps (STS-192) TDM is 40 Gbps (STS-768). Also, since the hierarchy is optimized for voice traffic, there are inherent inefficiencies when carrying data traffic with SONET frames. Some of these inefficiencies are shown in Table 1-3. DWDM, by contrast, can transport any protocol, including SONET, without special encapsulation.

Table 1-3 Ethernet in SONET Inefficiencies

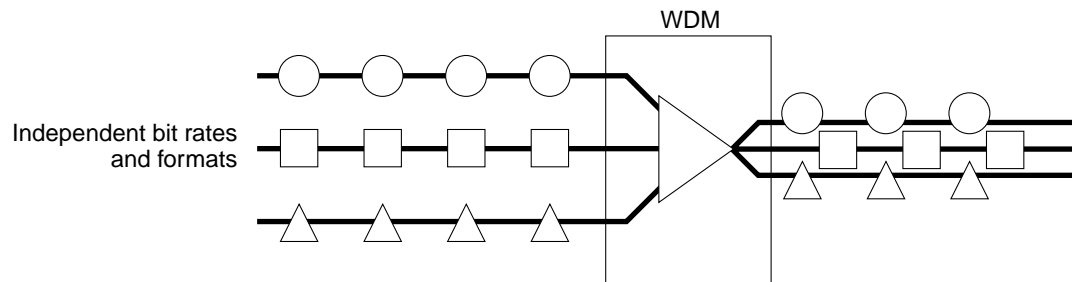
Ethernet	SONET/SDH Signal	Bit Rate	Wasted Bandwidth
10BASE-T (10 Mbps)	STS-1	51.8540 Mbps	80.709%
100BASE-T (100 Mbps)	STS-3/STM-1	155.520 Mbps	35.699%
1000BASE-T (1000 Mbps)	STS-48/STM-16	2488.32 Mbps	59.812%

To summarize, the demand placed on the transport infrastructure by bandwidth-hungry applications and the explosive growth of the Internet has exceeded the limits of traditional TDM. Fiber, which once promised seemingly unlimited bandwidth, is being exhausted, and the expense, complexity, and scalability limitations of the SONET infrastructure are becoming increasingly problematic.

Wavelength Division Multiplexing

WDM increases the carrying capacity of the physical medium (fiber) using a completely different method from TDM. WDM assigns incoming optical signals to specific frequencies of light (wavelengths, or lambdas) within a certain frequency band. This multiplexing closely resembles the way radio stations broadcast on different wavelengths without interfering with each other (see Figure 1-7). Because each channel is transmitted at a different frequency, we can select from them using a tuner. Another way to think about WDM is that each channel is a different color of light; several channels then make up a “rainbow.”

Figure 1-7 Increasing Capacity with WDM



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Note

The term *wavelength* is used instead of the term frequency to avoid confusion with other uses of frequency. Wavelength is often used interchangeably with *lambda* and *channel*.

In a WDM system, each of the wavelengths is launched into the fiber, and the signals are demultiplexed at the receiving end. Like TDM, the resulting capacity is an aggregate of the input signals, but WDM carries each input signal independently of the others. This means that each channel has its own dedicated bandwidth; all signals arrive at the same time, rather than being broken up and carried in time slots.

The difference between WDM and dense wavelength division multiplexing (DWDM) is fundamentally one of only degree. DWDM spaces the wavelengths more closely than does WDM, and therefore has a greater overall capacity. The limits of this spacing are not precisely known, and have probably not been reached, though systems are available in mid-year 2000 with a capacity of 128 lambdas on one fiber. DWDM has a number of other notable features, which are discussed in greater detail in the following chapters. These include the ability to amplify all the wavelengths at once without first converting them to electrical signals, and the ability to carry signals of different speeds and types simultaneously and transparently over the fiber (protocol and bit rate independence).



Note

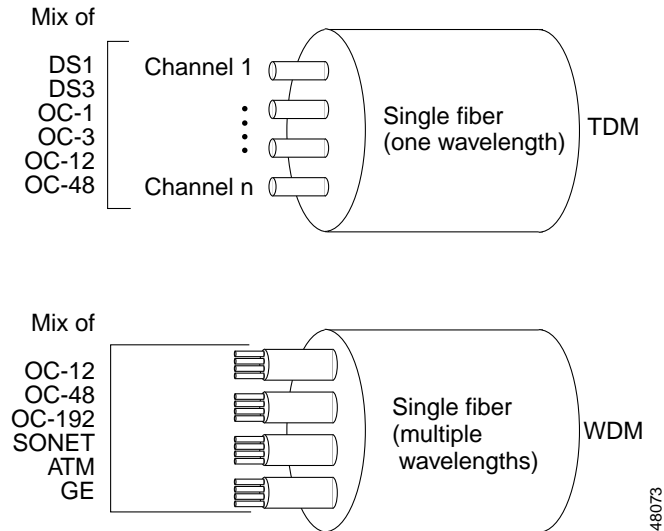
WDM and DWDM use single-mode fiber to carry multiple lightwaves of differing frequencies. This should not be confused with transmission over multimode fiber, in which light is launched into the fiber at different angles, resulting in different “modes” of light. A single wavelength is used in multimode transmission.

TDM and WDM Compared

SONET TDM takes synchronous and asynchronous signals and multiplexes them to a single higher bit rate for transmission at a single wavelength over fiber. Source signals may have to be converted from electrical to optical, or from optical to electrical and back to optical before being multiplexed. WDM

takes multiple optical signals, maps them to individual wavelengths, and multiplexes the wavelengths over a single fiber. Another fundamental difference between the two technologies is that WDM can carry multiple protocols without a common signal format, while SONET cannot. Some of the key differences between TDM and WDM are graphically illustrated in Figure 1-8.

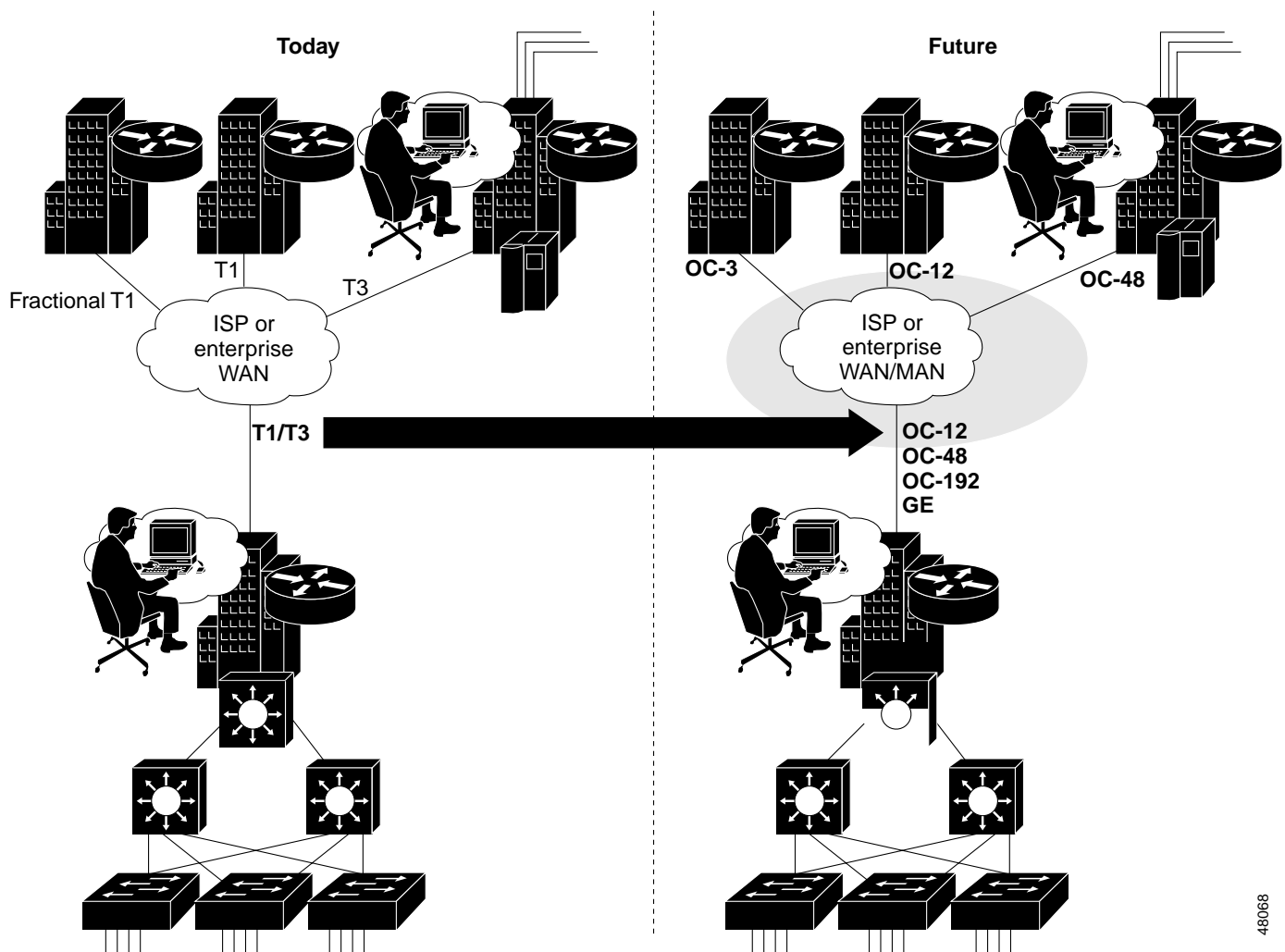
Figure 1-8 TDM and WDM Interfaces



Additional Drivers in Metropolitan Area Networks

Bandwidth, the chief driver in the long-haul market, is also a big driver in metropolitan area, access, and large enterprise networks (see Figure 1-9). In these types of networks additional applications driving demand for bandwidth include storage area networks (SANs), which make possible the serverless office, consolidation of data centers, and real-time transaction processing backup.

Figure 1-9 High-Speed Enterprise WAN Bandwidth Migration



There is also rapidly increasing demand on access networks, which function primarily to connect end users over low-speed connections, such as dial-up lines, DSL, cable, and wireless, to a local POP. These connections are typically aggregated and carried over a SONET ring, which at some point attaches to a local POP that serves as an Internet gateway for long hauls. Now, the growing demand for high-speed services is prompting service providers to transform the POP into a dynamic service-delivery center. As a result, it is increasingly likely that a customer now obtains many high-speed services directly from the POP, without ever using the core segment of the Internet.

Value of DWDM in the Metropolitan Area

DWDM is the clear winner in the backbone. It was first deployed on long-haul routes in a time of fiber scarcity. Then the equipment savings made it the solution of choice for new long-haul routes, even when ample fiber was available. While DWDM can relieve fiber exhaust in the metropolitan area, its value in this market extends beyond this single advantage. Alternatives for capacity enhancement exist, such as pulling new cable and SONET overlays, but DWDM can do more. What delivers additional value in the metropolitan market is DWDM's fast and flexible provisioning of protocol- and bit rate-transparent, data-centric, protected services, along with the ability to offer new and higher-speed services at less cost.

The need to provision services of varying types in a rapid and efficient manner in response to the changing demands of customers is a distinguishing characteristic of the metropolitan networks. With SONET, which is the foundation of the vast majority of existing MANs, service provisioning is a lengthy and complex process. Network planning and analysis, ADM provisioning, Digital Crossconnect System (DCS) reconfiguration, path and circuit verification, and service creation can take several weeks. By contrast, with DWDM equipment in place provisioning new service can be as simple as turning on another lightwave in an existing fiber pair.

Potential providers of DWDM-based services in metropolitan areas, where abundant fiber plant already exists or is being built, include incumbent local exchange carriers (ILECs), competitive local exchange carriers (CLECs), inter-exchange carriers (IXCs), Internet service providers (ISPs), cable companies, private network operators, and utility companies. Such carriers can often offer new services for less cost than older ones. Much of the cost savings is due to reducing unnecessary layers of equipment, which also lowers operational costs and simplifies the network architecture.

Carriers can create revenue today by providing protocol-transparent, high-speed LAN and SAN services to large organizations, as well as a mixture of lower-speed services (Token Ring, FDDI, Ethernet) to smaller organizations. In implementing an optical network, they are ensuring that they can play in the competitive field of the future.

Requirements in the Metropolitan Area

The requirements in the metropolitan market may differ in some respects from those in the long-haul network market, yet metropolitan networks are still just a geographically distinguished segment of the global network. What happens in the core must be supported right to the edge. IP, for example, is the dominant traffic type, so interworking with this layer is a requirement, while not ignoring other traffic (TDM). Network management is now of primary concern, and protection schemes that ensure high availability are a given.

Key requirements for DWDM systems in the MAN include the following:

- Multiprotocol support
- Scalability
- Reliability and availability
- Openness (interfaces, network management, standard fiber types, electromagnetic compatibility)
- Ease of installation and management
- Size and power consumption
- Cost effectiveness

Why DWDM?

From both technical and economic perspectives, the ability to provide potentially unlimited transmission capacity is the most obvious advantage of DWDM technology. The current investment in fiber plant can not only be preserved, but optimized by a factor of at least 32. As demands change, more capacity can be added, either by simple equipment upgrades or by increasing the number of lambdas on the fiber, without expensive upgrades. Capacity can be obtained for the cost of the equipment, and existing fiber plant investment is retained.

Bandwidth aside, DWDM's most compelling technical advantages can be summarized as follows:

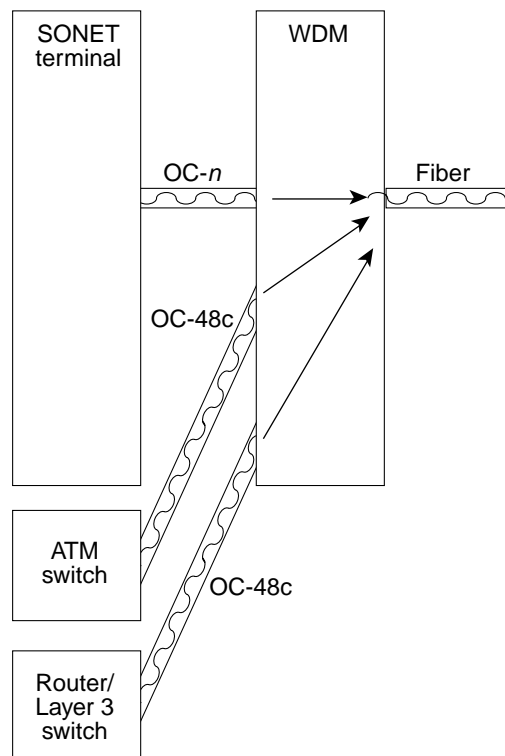
- **Transparency**—Because DWDM is a physical layer architecture, it can transparently support both TDM and data formats such as ATM, Gigabit Ethernet, ESCON, and Fibre Channel with open interfaces over a common physical layer.
- **Scalability**—DWDM can leverage the abundance of dark fiber in many metropolitan area and enterprise networks to quickly meet demand for capacity on point-to-point links and on spans of existing SONET/SDH rings.
- **Dynamic provisioning**—Fast, simple, and dynamic provisioning of network connections give providers the ability to provide high-bandwidth services in days rather than months.

In the following sections we discuss some additional advantages, including migration from SONET and reliability.

SONET with DWDM

By using DWDM as a transport for TDM, existing SONET equipment investments can be preserved. Often new implementations can eliminate layers of equipment. For example, SONET multiplexing equipment can be avoided altogether by interfacing directly to DWDM equipment from ATM and packet switches, where OC-48 interfaces are common (see Figure 1-10). Additionally, upgrades do not have to conform to specific bit rate interfaces, as with SONET, where aggregation of tributaries is locked into specific values.

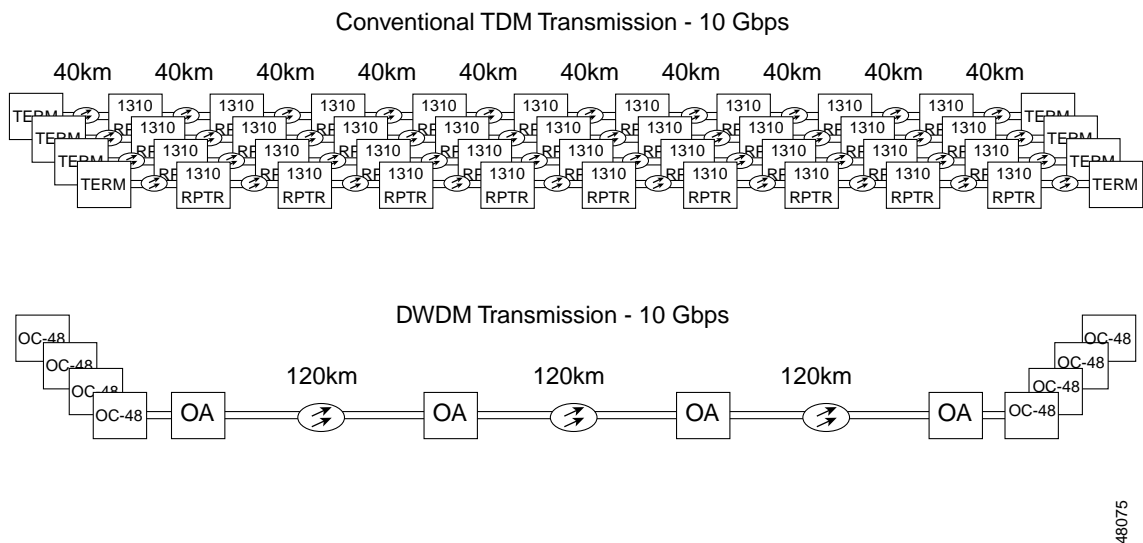
Figure 1-10 Direct SONET Interfaces from Switch to DWDM



Optical signals become attenuated as they travel through fiber and must be periodically regenerated in core networks. In SONET/SDH optical networks prior to the introduction of DWDM, each separate fiber carrying a single optical signal, typically at 2.5 Gbps, required a separate electrical regenerator every 60 to 100 km (37 to 62 mi). As additional fibers were “turned up” in a core network, the total cost of regenerators could become very large, because not only the cost of the regenerators themselves, but also the facilities to house and power them, had to be considered. The need to add regenerators also increased the time required to light new fibers.

The upper part of Figure 1-11 shows the infrastructure required to transmit at 10 Gbps (4 x OC-48 SR interfaces) across a span of 360 km (223 mi) using SONET equipment; the lower part of the figure shows the infrastructure required for the same capacity using DWDM. While optical amplifiers could be used in the SONET case to extend the distance of spans before having to boost signal power, there would still need to be an amplifier for each fiber. Because with DWDM all four signals can be transported on a single fiber pair (versus four), fewer pieces of equipment are required. Eliminating the expense of regenerators (RPTR) required for each fiber results in considerable savings.

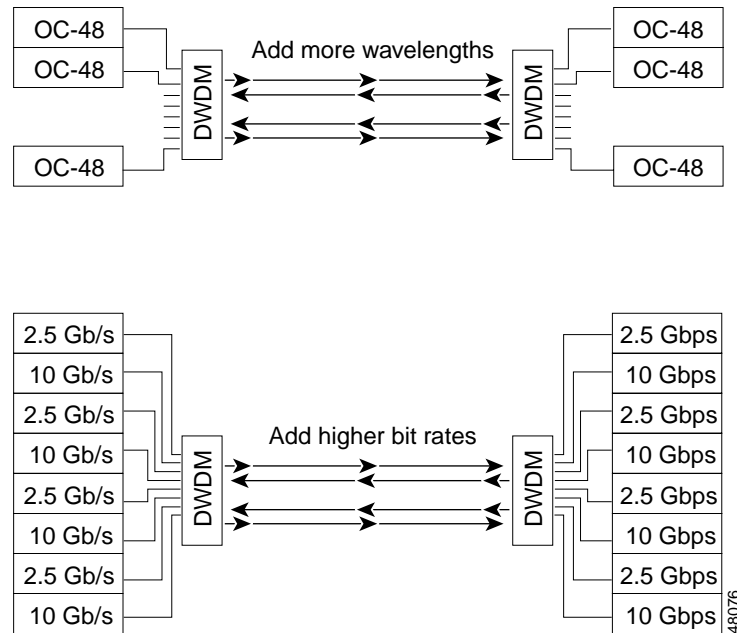
Figure 1-11 DWDM Eliminates Regenerators



A single optical amplifier can reamplify all the channels on a DWDM fiber without demultiplexing and processing them individually, with a cost approaching that of a single regenerator. The optical amplifier merely amplifies the signals; it does not reshape, retime or retransmit them as a regenerator does, so the signals may still need to be regenerated periodically. But depending on system design, signals can now be transmitted anywhere from 600 to thousands of kilometers without regeneration.

In addition to dramatically reducing the cost of regenerators, DWDM systems greatly simplify the expansion of network capacity. The only requirement is to install additional or higher bit-rate interfaces in the DWDM systems at either end of the fiber. In some cases it will only be necessary to increase the number of lambdas on the fiber by deploying existing interfaces, as shown in the upper half of Figure 1-12. The existing optical amplifiers amplify the new channel without additional regenerators. In the case of adding higher bit-rate interfaces, as shown in the lower half of Figure 1-12, fiber type can become a consideration. See the “Optical Fibers” section on page 2-6 for an overview of types of optical fibers and their uses.

Figure 1-12 Upgrading with DWDM



Although amplifiers are of great benefit in long-haul transport, they are often unnecessary in metropolitan networks. Where distances between network elements are relatively short, signal strength and integrity can be adequate without amplification. But with MANs expanding in deeper into long-haul reaches, amplifiers will become useful.

Enhancing Performance and Reliability

Today's metropolitan and enterprise networks support many mission-critical applications that require high availability, such as billing and accounting on mainframes or client-server installations in data centers. Continuous backups or reliable decentralized data processing and storage are essential. These applications, along with disaster recovery and parallel processing, have high requirements for performance and reliability. As enterprises out source data services and inter-LAN connectivity, the burden of service falls on the service provider rather than on the enterprise.

With DWDM, the transport network is theoretically unconstrained by the speed of available electronics. There is no need for optical-electrical-optical (OEO) conversion when using optical amplifiers, rather than regenerators, on the physical link. Although not yet prevalent, direct optical interfaces to DWDM equipment can also eliminate the need for an OEO function.

While optical amplifiers are a major factor in the ability to extend the effective range of DWDM, other factors also come into play. For example, DWDM is subject to dispersion and nonlinear effects. These effects are further discussed in the "Optical Fibers" section on page 2-6.

Many components, such as the optical add/drop multiplexer (OADM), are passive and therefore continue to work, even if there is a power cut. In addition, these components tend to have a very high mean time between failures (MTBF). Protection schemes implemented on DWDM equipment and in the network designs are at least as robust as those built into SONET. All these factors contribute to better performance and lower maintenance in the optical network.

Network Management Capability

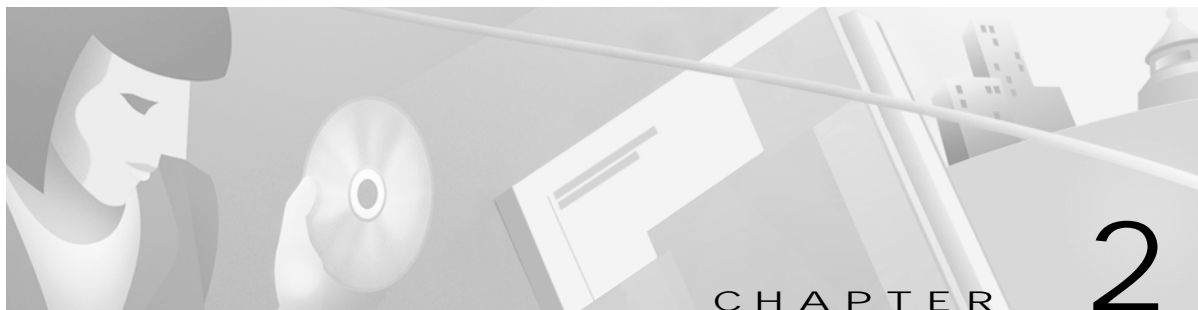
One of the primary advantages offered by SONET technology is the capability of the data communication channel (DCC). Used for operations functions, DCCs ship such things as alarms, administration data, signal control information, and maintenance messages. When SONET is transported over DWDM, DCCs continue to perform these functions between SONET network elements. In addition, a DWDM system can have its own management channel for the optical layer. For out-of-band management, an additional wavelength (for example, a 33rd wavelength in a 32-wavelength system) can be used as an optical supervisory channel. For inband management, a small amount of bandwidth (for example, 8 kHz) can be reserved for management on a per-channel basis.

Additional Benefits

The shift in the makeup of traffic from voice to data has important implications for the design and operation of carrier networks. The introduction of cell-switching technologies such as ATM and Frame Relay demonstrates the limitations of the narrow-band, circuit-switched network design, but the limits of these technologies are being reached. Data is no longer an add-on to the voice-centric network, but is central. There are fundamentally different requirements of a data-centric network; two of these are the aggregation model and the open versus proprietary interfaces.

Aggregation in a voice-centric network consists of multiplexing numerous times onto transmission facilities and at many points in the network. Aggregation in a data-centric network, by contrast, tends to happen at the edge. With OC-48 (and higher) interfaces readily available on cell and packet switches, it becomes possible to eliminate costly SONET multiplexing and digital cross-connect equipment. OC-48 connections can interface directly to DWDM equipment.

Finally, service providers and enterprises can respond more quickly to changing demands by allocating bandwidth on demand. The ability to provision services rapidly by providing wavelength on demand creates new revenue opportunities such as wavelength leasing (an alternative to leasing of physical links or bit rate-limited tunnels), disaster recovery, and optical VPNs.



Fundamentals of DWDM Technology

The emergence of DWDM is one of the most recent and important phenomena in the development of fiber optic transmission technology. In the following discussion we briefly trace the stages of fiber optic technology and the place of DWDM in that development. We then examine the functions and components of a DWDM system, including the enabling technologies, and conclude with a high-level description of the operation of a DWDM system.

This chapter contains the following major sections:

- Evolution of Fiber Optic Transmission, page 2-1
- Components and Operation, page 2-5
- Optical Fibers, page 2-6
- Light Sources and Detectors, page 2-13
- Optical Amplifiers, page 2-16
- Multiplexers and Demultiplexers, page 2-17
- Interfaces to DWDM, page 2-20
- Operation of a Transponder Based DWDM System, page 2-21

Evolution of Fiber Optic Transmission

The reality of fiber optic transmission had been experimentally proven in the nineteenth century, but the technology began to advance rapidly in the second half of the twentieth century with the invention of the fiberscope, which found applications in industry and medicine, such as in laparoscopic surgery.

After the viability of transmitting light over fiber had been established, the next step in the development of fiber optics was to find a light source that would be sufficiently powerful and narrow. The light-emitting diode (LED) and the laser diode proved capable of meeting these requirements. Lasers went through several generations in the 1960s, culminating with the semiconductor lasers that are most widely used in fiber optics today.

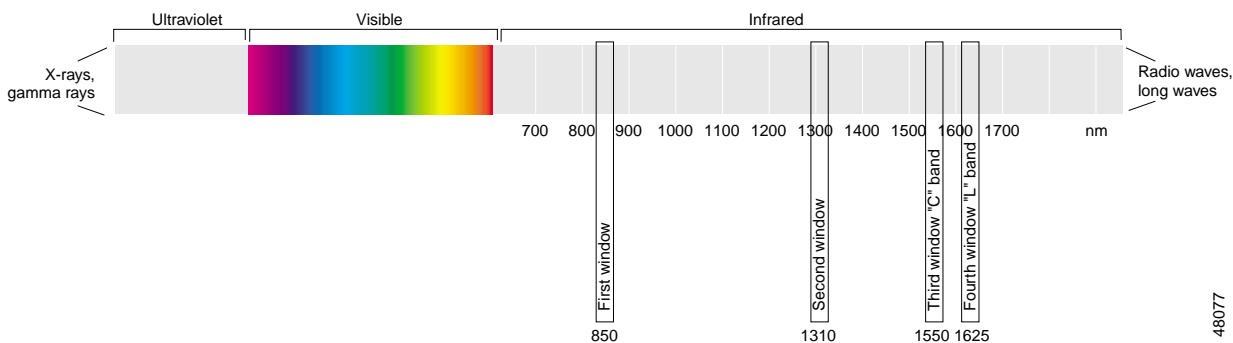
Light has an information-carrying capacity 10,000 times greater than the highest radio frequencies. Additional advantages of fiber over copper include the ability to carry signals over long distances, low error rates, immunity to electrical interference, security, and light weight.

Aware of these characteristics, researchers in the mid-1960s proposed that optical fiber might be a suitable transmission medium. There was an obstacle, however, and that was the loss of signal strength, or *attenuation*, seen in the glass they were working with. Finally, in 1970, Corning produced the first communication-grade fibers. With attenuation less than 20 decibels per kilometer (dB/km), this purified glass fiber exceeded the threshold for making fiber optics a viable technology.

Innovation at first proceeded slowly, as private and government monopolies that ran the telephone companies were cautious. AT&T first standardized transmission at DS3 speed (45 Mbps) for multimode fibers. Soon thereafter, single-mode fibers were shown to be capable of transmission rates 10 times that of the older type, as well as spans of 32 km (20 mi). In the early 1980s, MCI, followed by Sprint, adopted single-mode fibers for its long-distance network in the U.S.

Further developments in fiber optics are closely tied to the use of the specific regions on the optical spectrum where optical attenuation is low. These regions, called *windows*, lie between areas of high absorption. The earliest systems were developed to operate around 850 nm, the first window in silica-based optical fiber. A second window (S band), at 1310 nm, soon proved to be superior because of its lower attenuation, followed by a third window (C band) at 1550 nm with an even lower optical loss. Today, a fourth window (L band) near 1625 nm is under development and early deployment. These four windows are shown relative to the electromagnetic spectrum in Figure 2-1.

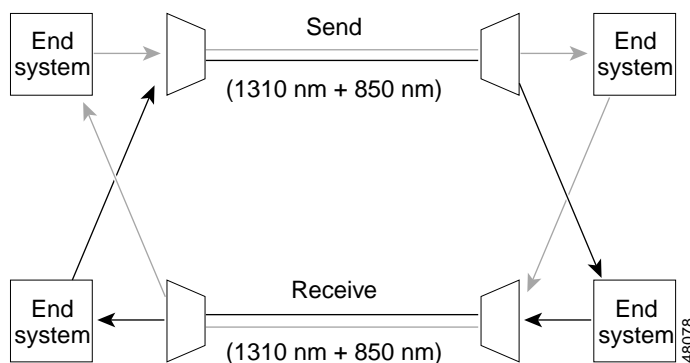
Figure 2-1 Wavelength Regions



Development of DWDM Technology

Early WDM began in the late 1980s using the two widely spaced wavelengths in the 1310 nm and 1550 nm (or 850 nm and 1310 nm) regions, sometimes called *wideband WDM*. Figure 2-2 shows an example of this simple form of WDM. Notice that one of the fiber pair is used to transmit and one is used to receive. This is the most efficient arrangement and the one most found in DWDM systems.

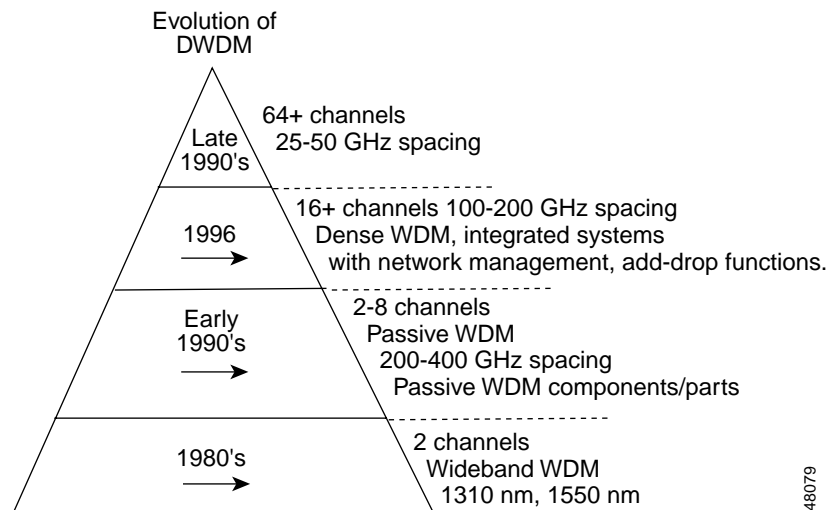
Figure 2-2 WDM with Two Channels



The early 1990s saw a second generation of WDM, sometimes called *narrowband WDM*, in which two to eight channels were used. These channels were now spaced at an interval of about 400 GHz in the 1550-nm window. By the mid-1990s, dense WDM (DWDM) systems were emerging with 16 to 40 channels and spacing from 100 to 200 GHz. By the late 1990s DWDM systems had evolved to the point where they were capable of 64 to 160 parallel channels, densely packed at 50 or even 25 GHz intervals.

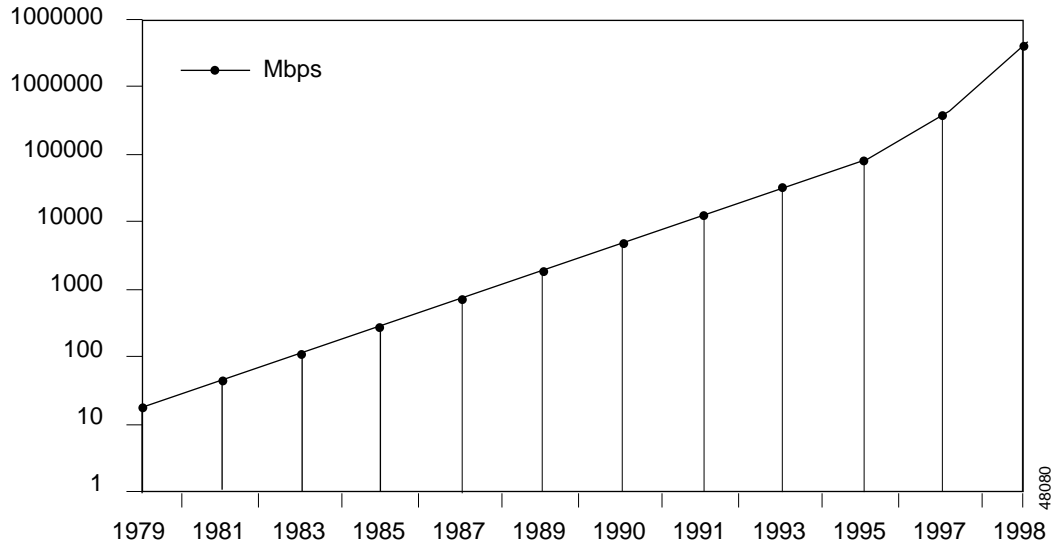
As Figure 2-3 shows, the progression of the technology can be seen as an increase in the number of wavelengths accompanied by a decrease in the spacing of the wavelengths. Along with increased density of wavelengths, systems also advanced in their flexibility of configuration, through add-drop functions, and management capabilities.

Figure 2-3 Evolution of DWDM



Increases in channel density resulting from DWDM technology have had a dramatic impact on the carrying capacity of fiber. In 1995, when the first 10 Gbps systems were demonstrated, the rate of increase in capacity went from a linear multiple of four every four years to four every year (see Figure 2-4).

Figure 2-4 Growth in Fiber Capacity



DWDM System Functions

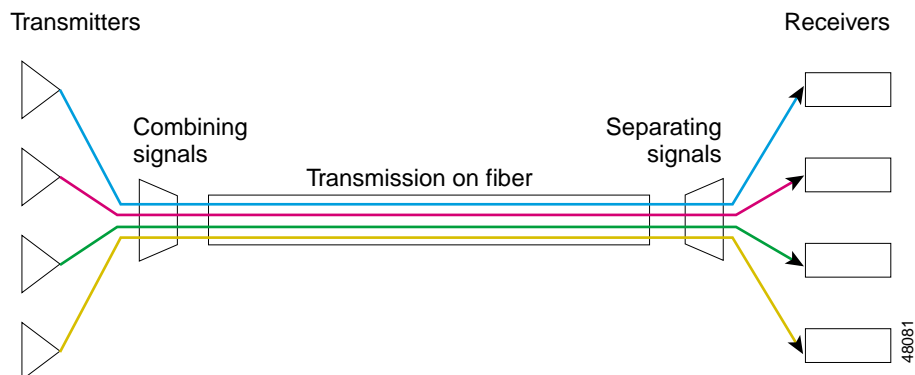
At its core, DWDM involves a small number of physical-layer functions. These are depicted in Figure 2-5, which shows a DWDM schematic for four channels. Each optical channel occupies its own wavelength.



Note

Wavelength is expressed (usually in nanometers) as an absolute point on the electromagnetic spectrum. The effective light at a given wavelength is confined narrowly *around* its central wavelength.

Figure 2-5 DWDM Functional Schematic



The system performs the following main functions:

- **Generating the signal**—The source, a solid-state laser, must provide stable light within a specific, narrow bandwidth that carries the digital data, modulated as an analog signal.
- **Combining the signals**—Modern DWDM systems employ multiplexers to combine the signals. There is some inherent loss associated with multiplexing and demultiplexing. This loss is dependent upon the number of channels but can be mitigated with optical amplifiers, which boost all the wavelengths at once without electrical conversion.
- **Transmitting the signals**—The effects of crosstalk and optical signal degradation or loss must be reckoned with in fiber optic transmission. These effects can be minimized by controlling variables such as channel spacings, wavelength tolerance, and laser power levels. Over a transmission link, the signal may need to be optically amplified.
- **Separating the received signals**—At the receiving end, the multiplexed signals must be separated out. Although this task would appear to be simply the opposite of combining the signals, it is actually more technically difficult.
- **Receiving the signals**—The demultiplexed signal is received by a photodetector.

In addition to these functions, a DWDM system must also be equipped with client-side interfaces to receive the input signal. This function is performed by transponders (see the “Interfaces to DWDM” section on page 2-20). On the DWDM side are interfaces to the optical fiber that links DWDM systems.

Enabling Technologies

Optical networking, unlike SONET/SDH, does not rely on electrical data processing. As such, its development is more closely tied to optics than to electronics. In its early form, as described previously, WDM was capable of carrying signals over two widely spaced wavelengths, and for a relatively short distance. To move beyond this initial state, WDM needed both improvements in existing technologies and invention of new technologies. Improvements in optical filters and narrowband lasers enabled DWDM to combine more than two signal wavelengths on a fiber. The invention of the flat-gain optical amplifier, coupled in line with the transmitting fiber to boost the optical signal, dramatically increased the viability of DWDM systems by greatly extending the transmission distance.

Other technologies that have been important in the development of DWDM include improved optical fiber with lower loss and better optical transmission characteristics, EDFAs, and devices such as fiber Bragg gratings used in optical add/drop multiplexers.

Components and Operation

DWDM is a core technology in an optical transport network. The essential components of DWDM can be classified by their place in the system as follows:

- On the transmit side, lasers with precise, stable wavelengths
- On the link, optical fiber that exhibits low loss and transmission performance in the relevant wavelength spectra, in addition to flat-gain optical amplifiers to boost the signal on longer spans
- On the receive side, photodetectors and optical demultiplexers using thin film filters or diffractive elements
- Optical add/drop multiplexers and optical cross-connect components

These and other components, along with their underlying technologies, are discussed in the following sections. While much of this information, particularly the pros and cons of various competing technologies, may be of more importance to a system designer than to an end user or network designer, it may also be of interest to other readers. Note as well that this is summary information and is not intended to be complete or authoritative. For in-depth information on components and underlying technologies, refer to the sources cited in the “Additional Reading” section on page vii.

Optical Fibers

The following discussion of DWDM components and technologies includes a refresher on optical fibers, with emphasis on their application for DWDM. Background information on subjects such as the properties of light and optical theory can be found in many readily available printed sources and online, for example, in the tutorial at <http://www.vislab.usyd.edu.au/photonics/fibres/index.html>.

How Fiber Works

The main job of optical fibers is to guide lightwaves with a minimum of attenuation (loss of signal). Optical fibers are composed of fine threads of glass in layers, called the core and cladding, that can transmit light at about two-thirds the speed of light in a vacuum. Though admittedly an oversimplification, the transmission of light in optical fiber is commonly explained using the principle of *total internal reflection*. With this phenomenon, 100 percent of light that strikes a surface is reflected. By contrast, a mirror reflects about 90 percent of the light that strikes it.

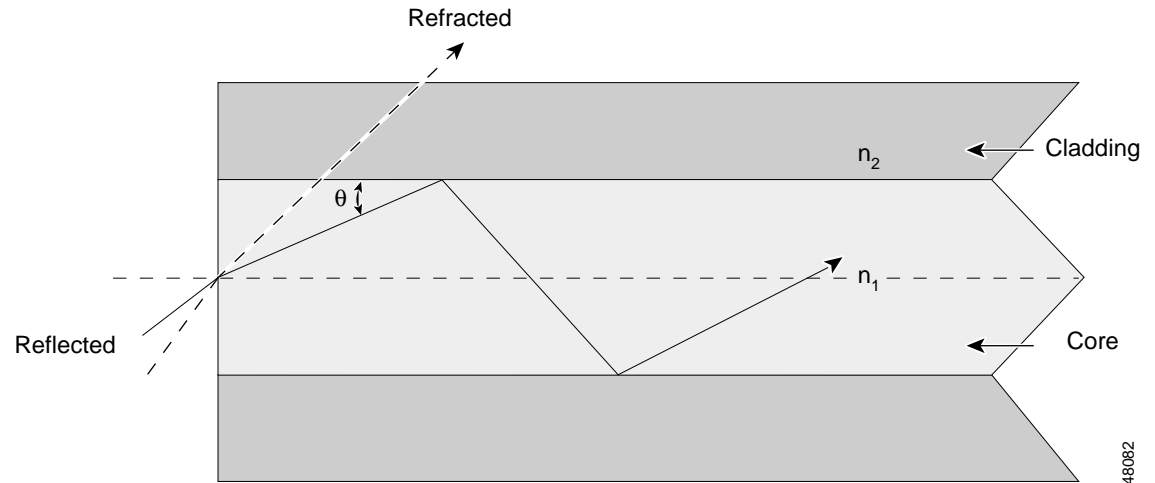
Light is either reflected (it bounces back) or refracted (its angle is altered while passing through a different medium) depending upon the angle of incidence (the angle at which light strikes the interface between an optically denser and optically thinner material).

Total internal reflection happens when the following conditions are met:

- Beams pass from a more dense to a less dense material. The difference between the optical density of a given material and a vacuum is the material's refractive index.
- The incident angle is less than the critical angle. The critical angle is the angle of incidence at which light stops being refracted and is instead totally reflected.

The principle of total internal reflection within a fiber core is illustrated in Figure 2-6. The core has a higher refractive index than the cladding, allowing the beam that strikes that surface at less than the critical angle to be reflected. The second beam does not meet the critical angle requirement and is refracted.

Figure 2-6 Principle of Total Internal Reflection

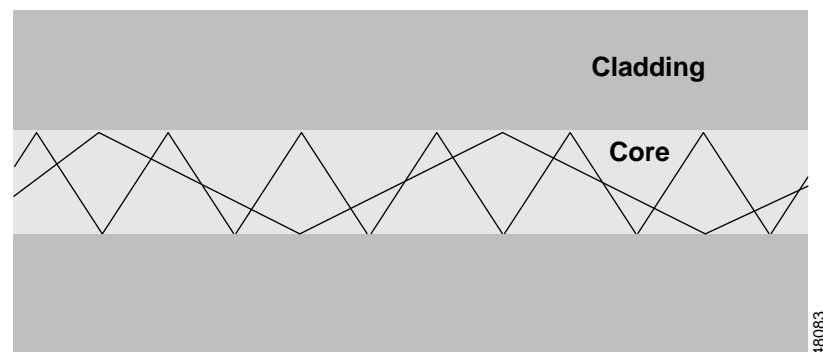


An optical fiber consists of two different types of highly pure, solid glass (silica)—the *core* and the *cladding*—that are mixed with specific elements, called *dopants*, to adjust their refractive indices. The difference between the refractive indices of the two materials causes most of the transmitted light to bounce off the cladding and stay within the core. The critical angle requirement is met by controlling the angle at which the light is injected into the fiber. Two or more layers of protective coating around the cladding ensure that the glass can be handled without damage.

Multimode and Single-Mode Fiber

There are two general categories of optical fiber in use today, multimode fiber and single-mode fiber. Multimode, the first type of fiber to be commercialized, has a larger core than single-mode fiber. It gets its name from the fact that numerous *modes*, or light rays, can be carried simultaneously through the waveguide. Figure 2-7 shows an example of light transmitted in the first type of multimode fiber, called *step-index*. Step-index refers to the fact that there is a uniform index of refraction throughout the core; thus there is a step in the refractive index where the core and cladding interface. Notice that the two modes must travel different distances to arrive at their destinations. This disparity between the times that the light rays arrive is called *modal dispersion*. This phenomenon results in poor signal quality at the receiving end and ultimately limits the transmission distance. This is why multimode fiber is not used in wide-area applications.

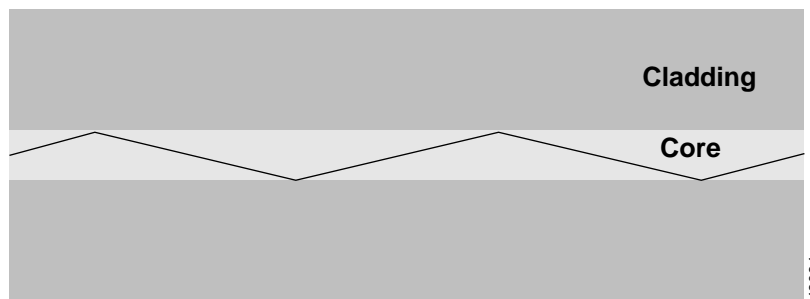
Figure 2-7 Reflected Light in Step-Index Multimode Fiber



To compensate for the dispersion drawback of step-index multimode fiber, graded-index fiber was invented. *Graded-index* refers to the fact that the refractive index of the core is graded—it gradually decreases from the center of the core outward. The higher refraction at the center of the core slows the speed of some light rays, allowing all the rays to reach their destination at about the same time and reducing modal dispersion.

The second general type of fiber, single-mode, has a much smaller core that allows only one mode of light at a time through the core (see Figure 2-8). As a result, the fidelity of the signal is better retained over longer distances, and modal dispersion is greatly reduced. These factors attribute to a higher bandwidth capacity than multimode fibers are capable of. For its large information-carrying capacity and low intrinsic loss, single-mode fibers are preferred for longer distance and higher bandwidth applications, including DWDM.

Figure 2-8 Reflected Light in Single-Mode Fiber



Single-Mode Fiber Designs

Designs of single-mode fiber have evolved over several decades. The three principle types and their ITU-T specifications are:

- Non-dispersion-shifted fiber (NDSF), G.652
- Dispersion-shifted fiber (DSF), G.653
- Non-zero dispersion-shifted fiber (NZ-DSF), G.655

As discussed earlier, and shown in Figure 2-1, there are four windows within the infrared spectrum that have been exploited for fiber transmission. The first window, near 850 nm, was used almost exclusively for short-range, multimode applications. Non-dispersion-shifted fibers, commonly called standard single-mode (SM) fibers, were designed for use in the second window, near 1310 nm. To optimize the fiber's performance in this window, the fiber was designed so that chromatic dispersion would be close to zero near the 1310-nm wavelength.

As optical fiber use became more common and the needs for greater bandwidth and distance increased, a third window, near 1550 nm, was exploited for single-mode transmission. The third window, or C band, offered two advantages: it had much lower attenuation, and its operating frequency was the same as that of the new erbium-doped fiber amplifiers (EDFAs). However, its dispersion characteristics were severely limiting. This was overcome to a certain extent by using narrower linewidth and higher power lasers. But because the third window had lower attenuation than the 1310-nm window, manufacturers came up with the dispersion-shifted fiber design, which moved the zero-dispersion point to the 1550-nm region. Although this solution now meant that the lowest optical attenuation and the zero-dispersion points coincided in the 1550-nm window, it turned out that there are destructive nonlinearities in optical fiber near the zero-dispersion point for which there is no effective compensation. Because of this limitation, these fibers are not suitable for DWDM applications.

The third type, non-zero dispersion-shifted fiber, is designed specifically to meet the needs of DWDM applications. The aim of this design is to make the dispersion low in the 1550-nm region, but not zero. This strategy effectively introduces a controlled amount of dispersion, which counters nonlinear effects such as four-wave mixing (see the “Other Nonlinear Effects” section on page 2-12) that can hinder the performance of DWDM systems.

Transmission Challenges

Transmission of light in optical fiber presents several challenges that must be dealt with. These fall into the following three broad categories:

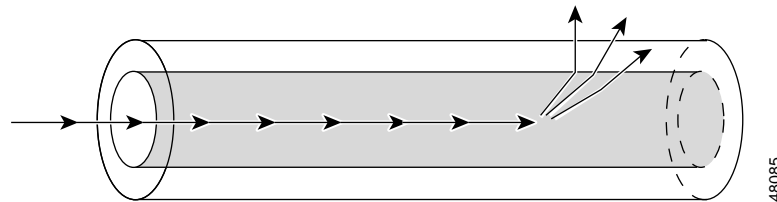
- Attenuation—decay of signal strength, or loss of light power, as the signal propagates through the fiber
- Chromatic dispersion—spreading of light pulses as they travel down the fiber
- Nonlinearities—cumulative effects from the interaction of light with the material through which it travels, resulting in changes in the lightwave and interactions between lightwaves

Each of these effects has several causes, not all of which affect DWDM. The discussion in the following sections addresses those causes that are relevant to DWDM.

Attenuation

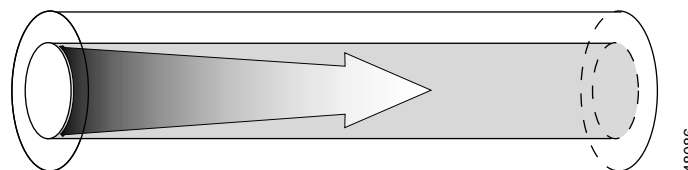
Attenuation in optical fiber is caused by intrinsic factors, primarily scattering and absorption, and by extrinsic factors, including stress from the manufacturing process, the environment, and physical bending. The most common form of scattering, *Rayleigh scattering*, is caused by small variations in the density of glass as it cools. These variations are smaller than the wavelengths used and therefore act as scattering objects (see Figure 2-9). Scattering affects short wavelengths more than long wavelengths and limits the use of wavelengths below 800 nm.

Figure 2-9 Rayleigh Scattering



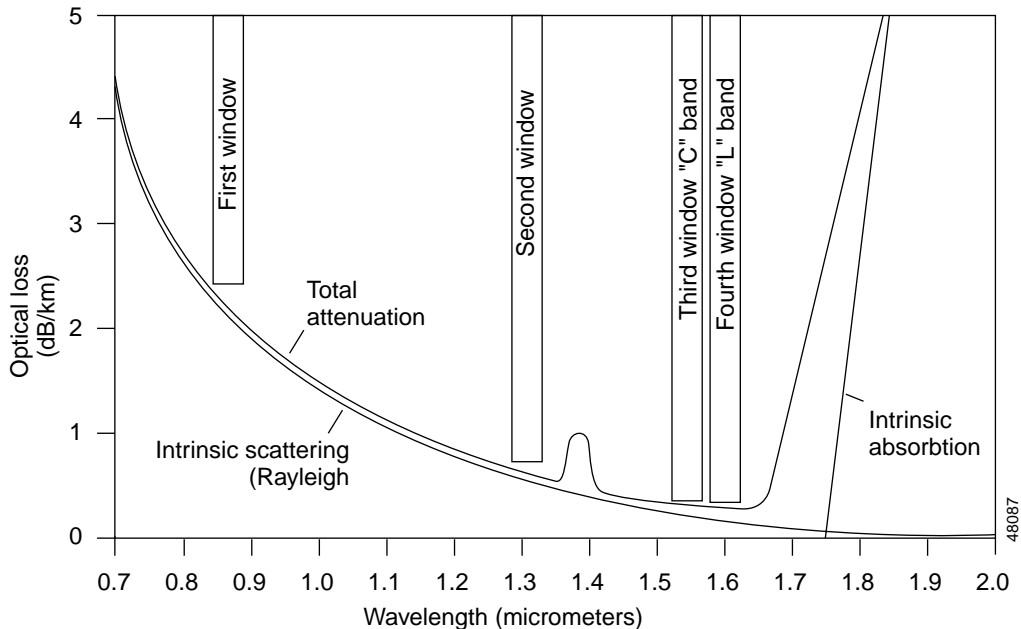
Attenuation due to absorption is caused by the intrinsic properties of the material itself, the impurities in the glass, and any atomic defects in the glass. These impurities absorb the optical energy, causing the light to become dimmer (see Figure 2-10). While Rayleigh scattering is important at shorter wavelengths, intrinsic absorption is an issue at longer wavelengths and increases dramatically above 1700 nm. However, absorption due to water peaks introduced in the fiber manufacturing process are being eliminated in some new fiber types.

Figure 2-10 Absorption



The primary factors affecting attenuation in optical fibers are the length of the fiber and the wavelength of the light. Figure 2-11 shows the loss in decibels per kilometer (dB/km) by wavelength from Rayleigh scattering, intrinsic absorption, and total attenuation from all causes.

Figure 2-11 Total Attenuation Curve

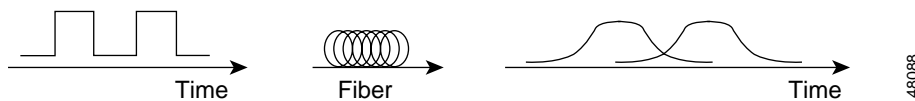


Attenuation in fiber is compensated primarily through the use of optical amplifiers, as described in the “Optical Amplifiers” section on page 2-16.

Dispersion

Dispersion is the spreading of light pulses as they travel down optical fiber. Dispersion results in distortion of the signal (see Figure 2-12), which limits the bandwidth of the fiber.

Figure 2-12 Principle of Dispersion



Two general types of dispersion affect DWDM systems. One of these effects, chromatic dispersion, is linear while the other, polarization mode dispersion (PMD), is nonlinear.

Chromatic Dispersion

Chromatic dispersion occurs because different wavelengths propagate at different speeds. The effect of chromatic dispersion increases as the square of the bit rate. In single-mode fiber, chromatic dispersion has two components, material dispersion and waveguide dispersion.

Material dispersion occurs when wavelengths travel at different speeds through the material. A light source, no matter how narrow, emits several wavelengths within a range. Thus, when this range of wavelengths travels through a medium, each individual wavelength arrives at a different time.

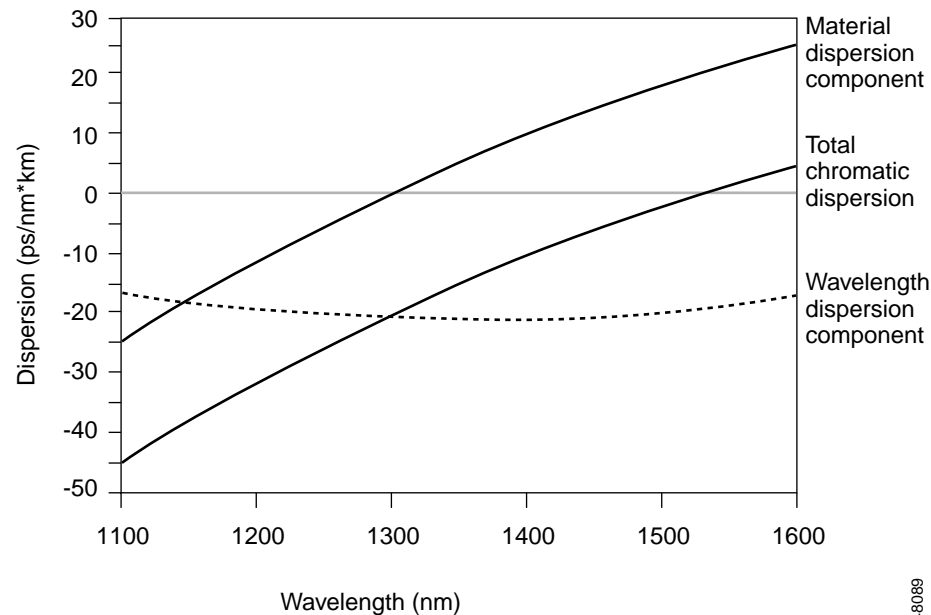
The second component of chromatic dispersion, waveguide dispersion, occurs because of the different refractive indices of the core and the cladding of fiber. The effective refractive index varies with wavelength as follows:

- At short wavelengths, the light is well confined within the core. Thus the effective refractive index is close to the refractive index of the core material.
- At medium wavelengths, the light spreads slightly into the cladding. This decreases the effective refractive index.
- At long wavelengths, much of the light spreads into the cladding. This brings the effective refractive index very close to that of the cladding.

This result of the phenomenon of waveguide dispersion is a propagation delay in one or more of the wavelengths relative to others.

Total chromatic dispersion, along with its components, is plotted by wavelength in Figure 2-13 for dispersion-shifted fiber. For non-dispersion-shifted fiber, the zero dispersion wavelength is 1310 nm.

Figure 2-13 Chromatic Dispersion



Though chromatic dispersion is generally not an issue at speeds below OC-48, it does increase with higher bit rates due to the spectral width required. New types of zero-dispersion-shifted fibers greatly reduce these effects. The phenomenon can also be mitigated with dispersion compensators.

Polarization Mode Dispersion

Most single-mode fibers support two perpendicular polarization modes, a vertical one and a horizontal one. Because these polarization states are not maintained, there occurs an interaction between the pulses that results in a smearing of the signal.

Polarization mode dispersion (PMD) is caused by ovality of the fiber shape as a result of the manufacturing process or from external stressors. Because stress can vary over time, PMD, unlike chromatic dispersion, is subject to change over time. PMD is generally not a problem at speeds below OC-192.

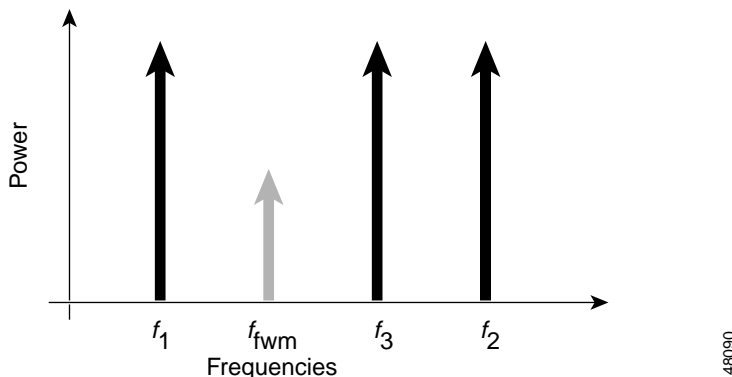
Other Nonlinear Effects

In addition to PMD, there are other nonlinear effects. Because nonlinear effects tend to manifest themselves when optical power is very high, they become important in DWDM.

Linear effects such as attenuation and dispersion can be compensated, but nonlinear effects *accumulate*. They are the fundamental limiting mechanisms to the amount of data that can be transmitted in optical fiber. The most important types of nonlinear effects are stimulated Brillouin scattering, stimulated Raman scattering, self-phase modulation, and four-wave mixing. In DWDM, four-wave mixing is the most critical of these types.

Four-wave mixing is caused by the nonlinear nature of the refractive index of the optical fiber. Nonlinear interactions among different DWDM channels creates sidebands that can cause interchannel interference. In Figure 2-14 three frequencies interact to produce a fourth frequency, resulting in cross-talk and signal-to-noise degradation.

Figure 2-14 Four-Wave Mixing



The effect of four-wave mixing is to limit the channel capacity of a DWDM system. Four-wave mixing cannot be filtered out, either optically or electrically, and increases with the length of the fiber. Due to its propensity for four-wave-mixing, DSF is unsuitable for WDM applications. This prompted the invention of NZ-DSF, which takes advantage of the fact that a small amount of chromatic dispersion can be used to mitigate four-wave mixing.

Summary

In the long-distance network, the majority of embedded fiber is standard single-mode (G.652) with high dispersion in the 1550-nm window, which limits the distance for OC-192 transmission. Dispersion can be mitigated to some extent, and at some cost, using dispersion compensators. Non-zero dispersion-shifted fiber can be deployed for OC-192 transport, but higher optical power introduces nonlinear effects.

In the short-haul network, PMD and nonlinear effects are not so critical as they are in long-haul systems, where higher speeds (OC-192 and higher) are more common. DWDM systems using optical signals of 2.5 Gbps or less are not subject to these nonlinear effects at short distances.

The major types of single-mode fibers and their application can be summarized as follows:

- Non-dispersion-shifted fiber (standard SM fiber)—accounts for greater than 95 percent of deployed plant; suitable for TDM (single-channel) use in the 1310-nm region or DWDM use in the 1550-nm region (with dispersion compensators). This type of fiber can also support 10 Gigabit Ethernet standard at distances over 300 meters.
- Dispersion-shifted fiber—suitable for TDM use in the 1550-nm region, but unsuitable for DWDM in this region.
- Non-zero dispersion-shifted fiber—good for both TDM and DWDM use in the 1550-nm region.
- Newer generation fibers—includes types that allow the energy to travel further into the cladding, creating a small amount of dispersion to counter four-wave mixing, and dispersion-flattened fibers, which permit use of wavelengths farther from the optimum wavelength without pulse spreading.



Note

As bit rates increase to 40 Gbps and beyond, the interdependence between system design and fiber design will become increasingly important for strategic planning.

Light Sources and Detectors

Light emitters and light detectors are active devices at opposite ends of an optical transmission system. Light sources, or light emitters, are transmit-side devices that convert electrical signals to light pulses. The process of this conversion, or modulation, can be accomplished by externally modulating a continuous wave of light or by using a device that can generate modulated light directly. Light detectors perform the opposite function of light emitters. They are receive-side opto-electronic devices that convert light pulses into electrical signals.

Light Emitters—LEDs and Lasers

The light source used in the design of a system is an important consideration because it can be one of the most costly elements. Its characteristics are often a strong limiting factor in the final performance of the optical link. Light emitting devices used in optical transmission must be compact, monochromatic, stable, and long-lasting.



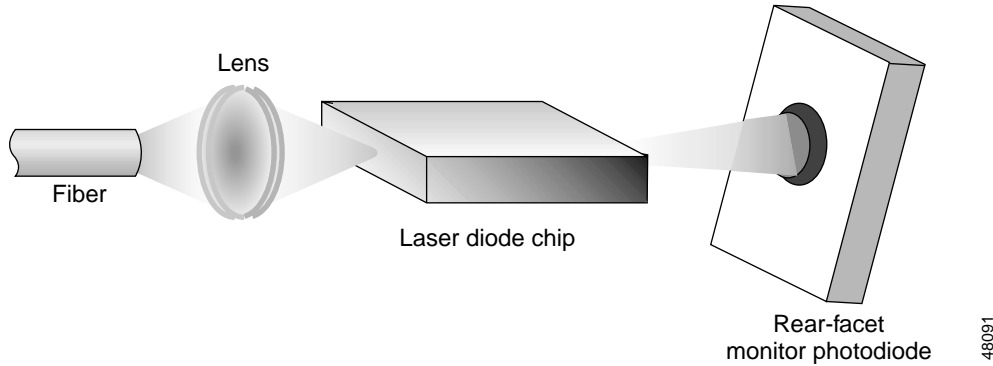
Note

Monochromatic is a relative term; in practice there are only light sources within a certain range. Stability of a light source is a measure of how constant its intensity and wavelength are.

Two general types of light emitting devices are used in optical transmission, light-emitting diodes (LEDs) and laser diodes, or semiconductor lasers. LEDs are relatively slow devices, suitable for use at speeds of less than 1 Gbps, they exhibit a relatively wide spectrum width, and they transmit light in a relatively wide cone. These inexpensive devices are often used in multimode fiber communications. Semiconductor lasers, on the other hand, have performance characteristics better suited to single-mode fiber applications.

Figure 2-15 shows the general principles of launching laser light into fiber. The laser diode chip emits light in one direction to be focused by the lens onto the fiber and in the other direction onto a photodiode. The photodiode, which is angled to reduce back reflections into the laser cavity, provides a way of monitoring the output of the lasers and providing feedback so that adjustments can be made.

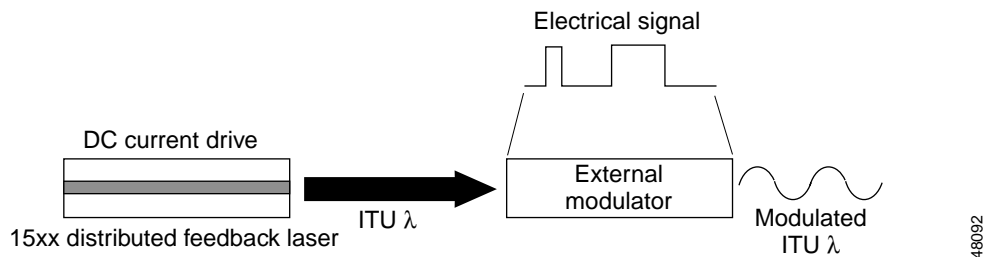
Figure 2-15 Typical Laser Design



Requirements for lasers include precise wavelength, narrow spectrum width, sufficient power, and control of *chirp* (the change in frequency of a signal over time). Semiconductor lasers satisfy nicely the first three requirements. Chirp, however, can be affected by the means used to modulate the signal.

In directly modulated lasers, the modulation of the light to represent the digital data is done internally. With external modulation, the modulation is done by an external device. When semiconductor lasers are directly modulated, chirp can become a limiting factor at high bit rates (above 10 Gbps). External modulation, on the other hand, helps to limit chirp. The external modulation scheme is depicted in Figure 2-16.

Figure 2-16 External Modulation of a Laser



Two types of semiconductor lasers are widely used, monolithic Fabry-Perot lasers, and distributed feedback (DFB) lasers. The latter type is particularly well suited for DWDM applications, as it emits a nearly monochromatic light, is capable of high speeds, has a favorable signal-to-noise ratio, and has superior linearity. DFB lasers also have center frequencies in the region around 1310 nm, and from 1520 to 1565 nm. The latter wavelength range is compatible with EDFAs. There are many other types and subtypes of lasers. Narrow spectrum tunable lasers are available, but their tuning range is limited to approximately 100-200 GHz. Under development are wider spectrum tunable lasers, which will be important in dynamically switched optical networks.

ITU Grid

Cooled DFB lasers are available in precisely selected wavelengths. The ITU draft standard G.692 defines a laser grid for point-to-point WDM systems based on 100-GHz wavelength spacings with a center wavelength of 1553.52 nm (see Table 2-1).

Table 2-1 ITU Grid

Frequency (THz ¹)	Wavelength (nm ²)	Frequency (THz)	Wavelength (nm)	Frequency (THz)	Wavelength (nm)
196.1	1528.77	164.6	1540.56	193.1	1552.52
196.0	1529.55	194.5	1541.35	193.0	1553.33
195.9	1530.33	194.4	1542.14	192.9	1554.13
195.8	1531.12	194.3	1542.94	195.8	1554.94
195.7	1531.9	194.2	1543.73	192.7	1555.75
195.6	1532.68	194.1	1544.53	192.6	1556.56
195.5	1533.47	194.0	1545.32	195.5	1557.36
195.4	1534.25	193.9	1546.12	192.4	1558.17
195.3	1535.04	193.8	1546.92	192.3	1558.98
195.2	1535.82	193.7	1547.72	192.2	1559.79
195.1	1536.61	193.6	1548.51	192.1	1560.61
195.0	1537.40	193.5	1549.32	192.0	1561.42
194.9	1538.19	192.4	1550.12	191.9	1562.23
194.8	1538.98	193.3	1550.92	191.8	1563.05
194.7	1539.77	193.2	1551.72	191.7	1563.86

1. THz = terahertz
2. nm = nanometer

While this grid defines a standard, users are free to use the wavelengths in arbitrary ways and to choose from any part of the spectrum. In addition, manufacturers can deviate from the grid by extending the upper and lower bounds or by spacing the wavelengths more closely, typically at 50 GHz, to double the number of channels. The closer the spacing, the more channel crosstalk results. In addition, the impact of some fiber nonlinearities, such as FWM, increases. Spacing at 50 GHz also limits the maximum data rate per wavelength to 10 Gbps. The implications of the flexibility in implementation are twofold: There is no guarantee of compatibility between two end systems from different vendors, and there exists a design trade-off in the spacing of wavelengths between number of channels and maximum bit rate.

Light Detectors

On the receive end, it is necessary to recover the signals transmitted at different wavelengths on the fiber. Because photodetectors are by nature wideband devices, the optical signals are demultiplexed before reaching the detector.

Two types of photodetectors are widely deployed, the positive-intrinsic-negative (PIN) photodiode and the avalanche photodiode (APD). PIN photodiodes work on principles similar to, but in the reverse of, LEDs. That is, light is absorbed rather than emitted, and photons are converted to electrons in a 1:1 relationship. APDs are similar devices to PIN photodiodes, but provide gain through an amplification process: One photon acting on the device releases many electrons. PIN photodiodes have many advantages, including low cost and reliability, but APDs have higher receive sensitivity and accuracy. However, APDs are more expensive than PIN photodiodes, they can have very high current requirements, and they are temperature sensitive.

Optical Amplifiers

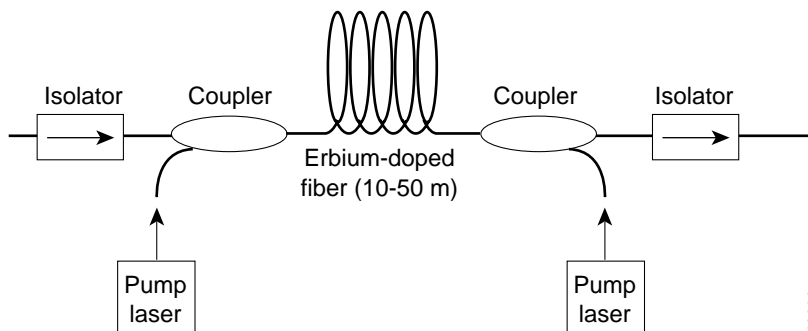
Due to attenuation, there are limits to how long a fiber segment can propagate a signal with integrity before it has to be regenerated. Before the arrival of optical amplifiers (OAs), there had to be a repeater for every signal transmitted, as discussed earlier and shown in Figure 1-11. The OA has made it possible to amplify all the wavelengths at once and without optical-electrical-optical (OEO) conversion. Besides being used on optical links, optical amplifiers also can be used to boost signal power after multiplexing or before demultiplexing, both of which can introduce loss into the system.

Erbium-Doped Fiber Amplifier

By making it possible to carry the large loads that DWDM is capable of transmitting over long distances, the EDFA was a key enabling technology. At the same time, it has been a driving force in the development of other network elements and technologies.

Erbium is a rare-earth element that, when excited, emits light around 1.54 micrometers—the low-loss wavelength for optical fibers used in DWDM. Figure 2-17 shows a simplified diagram of an EDFA. A weak signal enters the erbium-doped fiber, into which light at 980 nm or 1480 nm is injected using a pump laser. This injected light stimulates the erbium atoms to release their stored energy as additional 1550-nm light. As this process continues down the fiber, the signal grows stronger. The spontaneous emissions in the EDFA also add noise to the signal; this determines the noise figure of an EDFA.

Figure 2-17 Erbium-Doped Fiber Amplifier Design



The key performance parameters of optical amplifiers are gain, gain flatness, noise level, and output power. EDFAs are typically capable of gains of 30 dB or more and output power of +17 dB or more. The target parameters when selecting an EDFA, however, are low noise and flat gain. Gain should be flat because all signals must be amplified uniformly. While the signal gain provided with EDFA technology is inherently wavelength-dependent, it can be corrected with gain flattening filters. Such filters are often built into modern EDFAs.

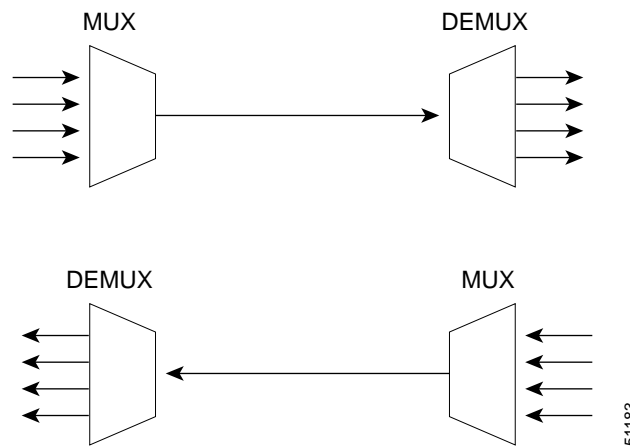
Low noise is a requirement because noise, along with signal, is amplified. Because this effect is cumulative, and cannot be filtered out, the signal-to-noise ratio is an ultimate limiting factor in the number of amplifiers that can be concatenated and, therefore, the length of a single fiber link. In practice, signals can travel for up to 120 km (74 mi) between amplifiers. At longer distances of 600 to 1000 km (372 to 620 mi) the signal must be regenerated. That is because the optical amplifier merely amplifies the signals and does not perform the 3R functions (reshape, retime, retransmit). EDFAs are available for the C-band and the L-band.

Multiplexers and Demultiplexers

Because DWDM systems send signals from several sources over a single fiber, they must include some means to combine the incoming signals. This is done with a multiplexer, which takes optical wavelengths from multiple fibers and converges them into one beam. At the receiving end the system must be able to separate out the components of the light so that they can be discreetly detected. Demultiplexers perform this function by separating the received beam into its wavelength components and coupling them to individual fibers. Demultiplexing must be done before the light is detected, because photodetectors are inherently broadband devices that cannot selectively detect a single wavelength.

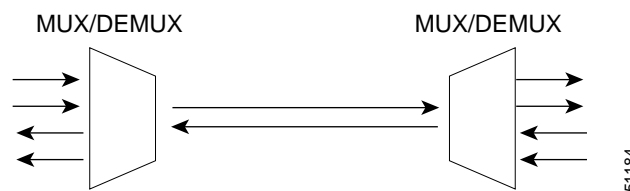
In a unidirectional system (see Figure 2-18), there is a multiplexer at the sending end and a demultiplexer at the receiving end. Two system would be required at each end for bidirectional communication, and two separate fibers would be needed.

Figure 2-18 Multiplexing and Demultiplexing in a Unidirectional System



In a bidirectional system, there is a multiplexer/demultiplexer at each end (see Figure 2-19) and communication is over a single fiber pair.

Figure 2-19 Multiplexing and Demultiplexing in a Bidirectional System

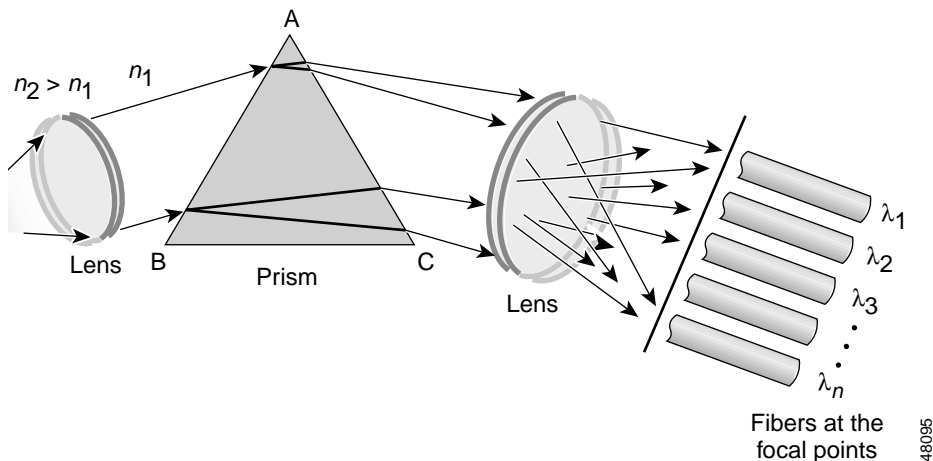


Multiplexers and demultiplexers can be either passive or active in design. Passive designs are based on prisms, diffraction gratings, or filters, while active designs combine passive devices with tunable filters. The primary challenges in these devices is to minimize cross-talk and maximize channel separation. Cross-talk is a measure of how well the channels are separated, while channel separation refers to the ability to distinguish each wavelength.

Techniques for Multiplexing and Demultiplexing

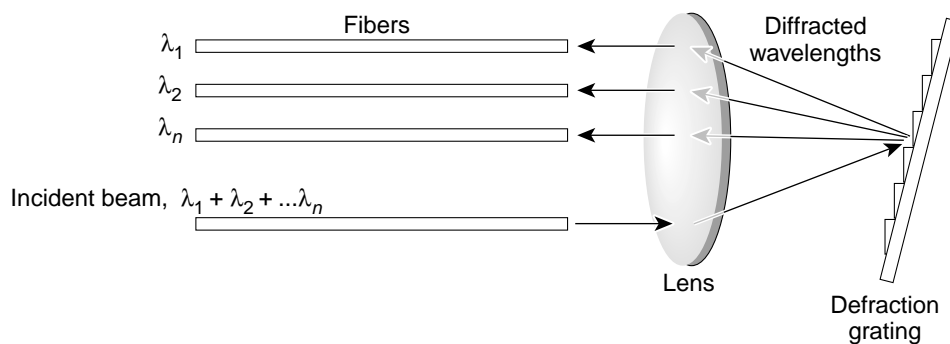
A simple form of multiplexing or demultiplexing of light can be done using a prism. Figure 2-20 demonstrates the demultiplexing case. A parallel beam of polychromatic light impinges on a prism surface; each component wavelength is refracted differently. This is the “rainbow” effect. In the output light, each wavelength is separated from the next by an angle. A lens then focuses each wavelength to the point where it needs to enter a fiber. The same components can be used in reverse to multiplex different wavelengths onto one fiber.

Figure 2-20 Prism Refraction Demultiplexing



Another technology is based on the principles of diffraction and of optical interference. When a polychromatic light source impinges on a diffraction grating (see Figure 2-21), each wavelength is diffracted at a different angle and therefore to a different point in space. Using a lens, these wavelengths can be focused onto individual fibers.

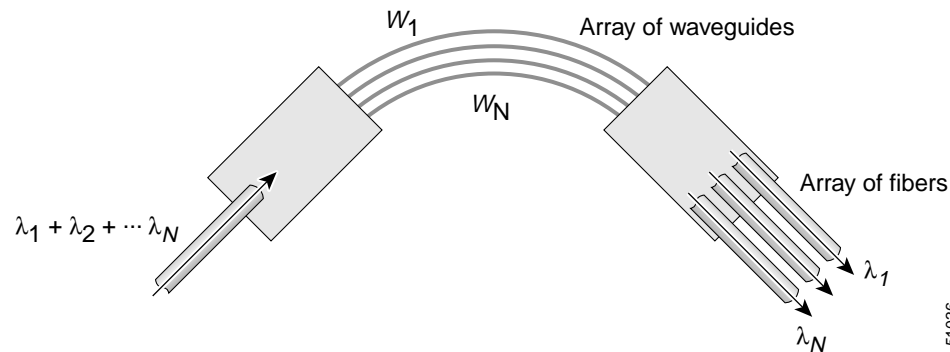
Figure 2-21 Waveguide Grating Diffraction



Arrayed waveguide gratings (AWGs) are also based on diffraction principles. An AWG device, sometimes called an optical waveguide router or waveguide grating router, consists of an array of curved-channel waveguides with a fixed difference in the path length between adjacent channels (see Figure 2-22). The waveguides are connected to cavities at the input and output. When the light enters the input cavity, it is diffracted and enters the waveguide array. There the optical length difference of

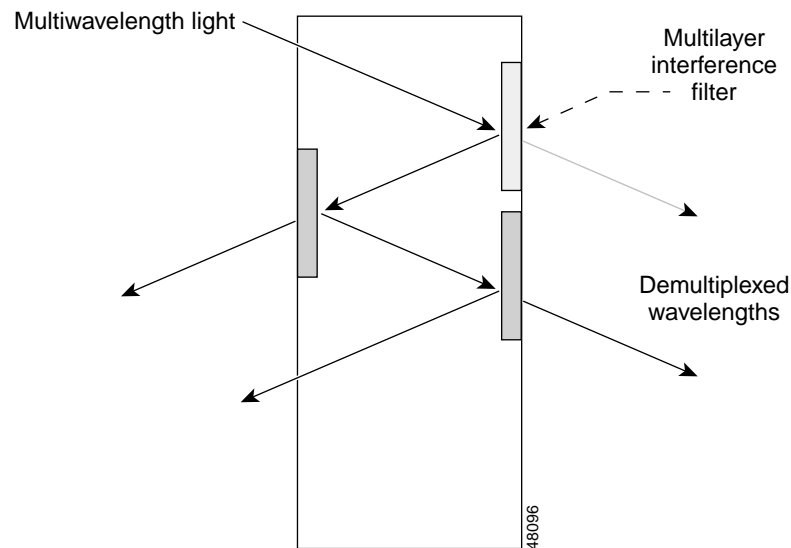
each waveguide introduces phase delays in the output cavity, where an array of fibers is coupled. The process results in different wavelengths having maximal interference at different locations, which correspond to the output ports.

Figure 2-22 Arrayed Waveguide Grating



A different technology uses interference filters in devices called *thin film filters* or *multilayer interference filters*. By positioning filters, consisting of thin films, in the optical path, wavelengths can be sorted out (demultiplexed). The property of each filter is such that it transmits one wavelength while reflecting others. By cascading these devices, many wavelengths can be demultiplexed (see Figure 2-23).

Figure 2-23 Multilayer Interference Filters



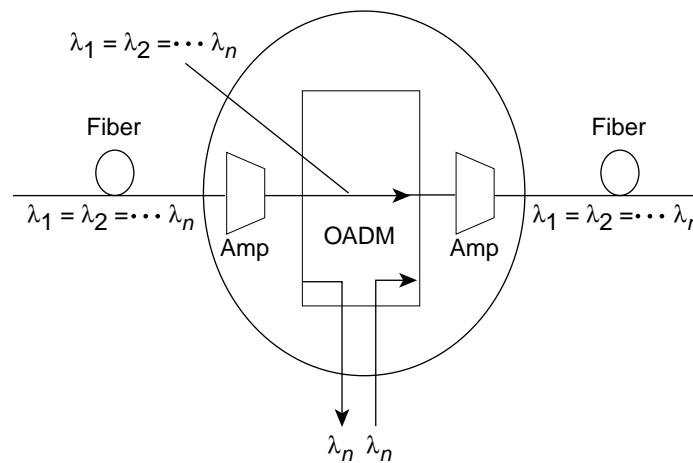
Of these designs, the AWG and thin film interference filters are gaining prominence. Filters offer good stability and isolation between channels at moderate cost, but with a high insertion loss. AWGs are polarization-dependent (which can be compensated), and they exhibit a flat spectral response and low insertion loss. A potential drawback is that they are temperature sensitive such that they may not be practical in all environments. Their big advantage is that they can be designed to perform multiplexing and demultiplexing operations simultaneously. AWGs are also better for large channel counts, where the use of cascaded thin film filters is impractical.

Optical Add/Drop Multiplexers

Between multiplexing and demultiplexing points in a DWDM system, as shown in Figure 2-18, there is an area in which multiple wavelengths exist. It is often desirable to be able to remove or insert one or more wavelengths at some point along this span. An optical add/drop multiplexer (OADM) performs this function. Rather than combining or separating all wavelengths, the OADM can remove some while passing others on. OADMs are a key part of moving toward the goal of all-optical networks.

OADMs are similar in many respects to SONET ADM, except that only optical wavelengths are added and dropped, and no conversion of the signal from optical to electrical takes place. Figure 2-24 is a schematic representation of the add-drop process. This example includes both pre- and post-amplification; these components that may or may not be present in an OADM, depending upon its design.

Figure 2-24 *Selectively Removing and Adding Wavelengths*



48097

There are two general types of OADMs. The first generation is a fixed device that is physically configured to drop specific predetermined wavelengths while adding others. The second generation is reconfigurable and capable of dynamically selecting which wavelengths are added and dropped.

Thin-film filters have emerged as the technology of choice for OADMs in current metropolitan DWDM systems because of their low cost and stability. For the emerging second generation of OADMs, other technologies, such as tunable fiber gratings and circulators, will come into prominence.

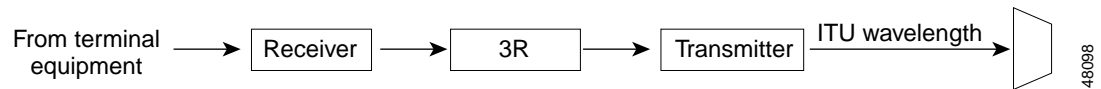
Interfaces to DWDM

Most DWDM systems support standard SONET/SDH short-reach optical interfaces to which any SONET/SDH compliant client device can attach. In today's long-haul WDM systems, this is most often an OC-48c/STM-16c interface operating at the 1310-nm wavelength. In addition, other interfaces important in metropolitan area and access networks are commonly supported: Ethernet (including Fast Ethernet and Gigabit Ethernet), ESCON, Sysplex Timer and Sysplex Coupling Facility Links, and Fibre Channel. The new 10 Gigabit Ethernet standard is supported using a very short reach (VSR) OC-192 interface over MM fiber between 10 Gigabit Ethernet and DWDM equipment.

On the client side there can be SONET/SDH terminals or ADMs, ATM switches, or routers. By converting incoming optical signals into the precise ITU-standard wavelengths to be multiplexed, *transponders* are currently a key determinant of the openness of DWDM systems.

Within the DWDM system a transponder converts the client optical signal from back to an electrical signal and performs the 3R functions (see Figure 2-25). This electrical signal is then used to drive the WDM laser. Each transponder within the system converts its client's signal to a slightly different wavelength. The wavelengths from all of the transponders in the system are then optically multiplexed. In the receive direction of the DWDM system, the reverse process takes place. Individual wavelengths are filtered from the multiplexed fiber and fed to individual transponders, which convert the signal to electrical and drive a standard interface to the client.

Figure 2-25 Transponder Functions

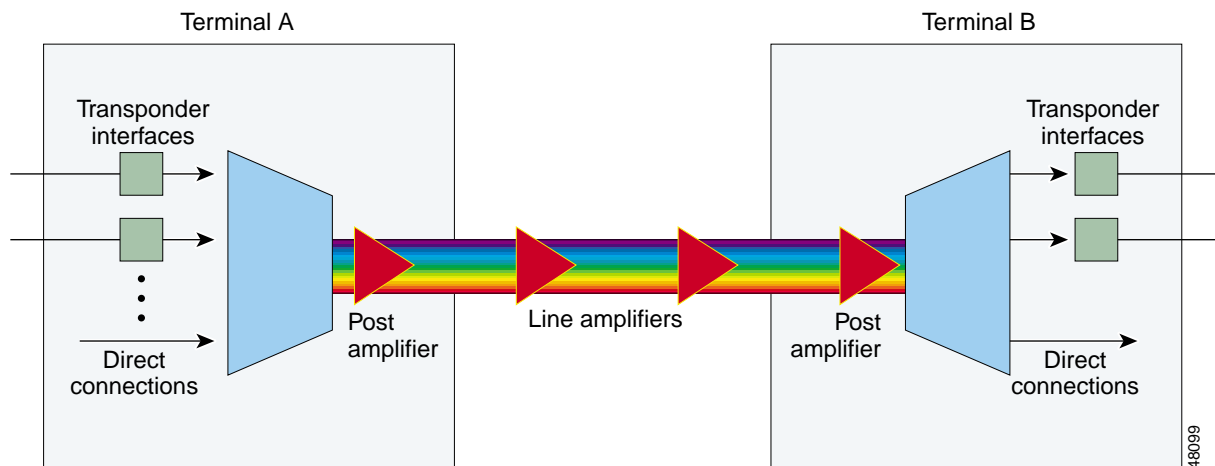


Future designs include passive interfaces, which accept the ITU-compliant light directly from an attached switch or router with an optical interface.

Operation of a Transponder Based DWDM System

Figure 2-26 shows the end-to-end operation of a unidirectional DWDM system.

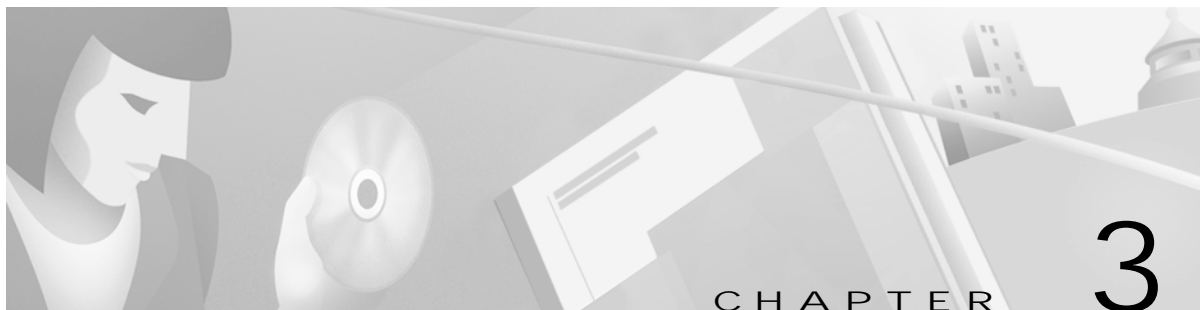
Figure 2-26 Anatomy of a DWDM System



The following steps describe the system shown in Figure 2-26:

1. The transponder accepts input in the form of standard single-mode or multimode laser. The input can come from different physical media and different protocols and traffic types.
2. The wavelength of each input signal is mapped to a DWDM wavelength.
3. DWDM wavelengths from the transponder are multiplexed into a single optical signal and launched into the fiber. The system might also include the ability to accept direct optical signals to the multiplexer; such signals could come, for example, from a satellite node.
4. A post-amplifier boosts the strength of the optical signal as it leaves the system (optional).
5. Optical amplifiers are used along the fiber span as needed (optional).
6. A pre-amplifier boosts the signal before it enters the end system (optional).

7. The incoming signal is demultiplexed into individual DWDM lambdas (or wavelengths).
8. The individual DWDM lambdas are mapped to the required output type (for example, OC-48 single-mode fiber) and sent out through the transponder.



DWDM in Metropolitan Area Networks

The long distances made possible by advances in technologies such as optical amplifiers, dispersion compensators, and new fiber types, resulted in the initial deployment of DWDM technology in the long-haul transoceanic and terrestrial networks. Once these technologies became commercially viable in the long-haul market, it was the next logical step to deploy them in the metropolitan area and, eventually, in the access networks using hybrid architectures of fiber and coaxial media.

We begin the following discussion by considering the main transport and network technologies used in metropolitan networks. We then briefly explore some of the potential applications for DWDM in these networks and examine the topologies that can be deployed. We continue by examining the protection mechanisms and schemes that are available to ensure reliability, and we conclude with a look at the future of optical networking.

This chapter contains the following major sections:

- Technologies in the Metropolitan Market, page 3-1
- Applications and Services in the MAN, page 3-5
- Topologies and Protection Schemes for DWDM, page 3-9
- Practical Considerations in Deploying DWDM, page 3-13
- Future of DWDM, page 3-14

Technologies in the Metropolitan Market

Numerous technologies for transport and encapsulation of data have been advocated in the metropolitan market. A characteristic of these networks, as noted earlier, is that they are called upon to support a variety of older and new traffic types and rates. Overall, however, there is a trend toward using a common optical layer for transporting digital data.

SONET/SDH

SONET/SDH has been the foundation for MANs over the last decade, serving as the fundamental transport layer for both TDM-based circuit switched network and most overlay data networks. While SONET/SDH has evolved into a very resilient technology, it remains fairly expensive to implement. Inherent inefficiencies in adapting data services to the voice-optimized hierarchy and an inflexible multiplexing hierarchy remain problematic. More importantly, capacity scaling limitations—OC-768 may be the practical limit of SONET/SDH—and unresponsiveness to bursty IP traffic make any TDM-based technology a poor choice for the future.

ATM

Many service providers favor ATM because it can encapsulate different protocols and traffic types into a common format for transmission over a SONET infrastructure. Meanwhile the data networking world, which is overwhelmingly IP-oriented, favors packet over SONET (POS), which obviates the costly ATM intermediate layer. Advancements in IP, combined with the scaling capacity of gigabit and multigigabit routers, make it possible to envisage an IP-based network that is well suited for carrying primarily data traffic, and secondarily voice.

Nevertheless ATM remains strong in the metropolitan area. It can accommodate higher speed line interfaces and provide managed virtual circuit services while offering traffic management capabilities. Thus ATM edge devices are commonly used to terminate traffic, including VoIP, DSL, and Frame Relay.

Gigabit Ethernet

Gigabit Ethernet (GE) is a proven technology for easy migration from and integration into traditional Ethernet. It is relatively inexpensive compared to other technologies that offer the same transmission rate, but does not provide quality of service (QoS) or fault tolerance on its own. When confined to point-to-point topologies, collisions and carrier sense multiple access (CSMA) are not of concern, resulting in more effective use of the full bandwidth. Because the optical physical layer can support much longer distances than traditional Category 5 cable, Gigabit Ethernet over fiber (1000BASE-LX, for example) can be extended into the wide-area realm using DWDM.

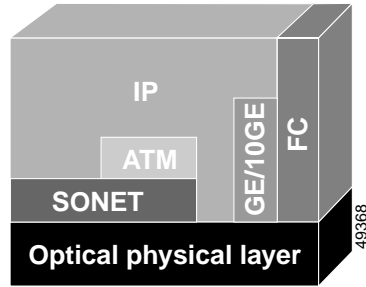
The latest advancement in Ethernet technology, 10 Gigabit Ethernet, is being driven by a need to interconnect Ethernet LANs operating at 10, 100, or 1000 Mbps. Ten Gigabit Ethernet can be used for aggregating slower access links, in the backbone networks, and for WAN access. Using 1550-nm serial lasers, distances of 40 to 80 km (25 to 50 mi) are possible with 10 Gigabit Ethernet over standard SM fiber. With such technology, service providers can build simple Ethernet networks over dark fiber without SONET or ATM and provision high-speed 10/100/1000 Mbps services at very low cost. In addition, a very short reach (VSR) OC-192 interface can be used to connect 10 Gigabit Ethernet to DWDM equipment over MM fiber.

Ethernet offers the technical advantages of a proven, adaptable, reliable, and uncomplicated technology. Implementations are standard and interoperable, and cost is much less than SONET or ATM. Architecturally, Ethernet's advantage is its emerging potential to serve as a scalable, end-to-end solution. Network management can also be improved by using Ethernet across the MAN and WAN.

IP

Clearly, as traditional circuit-switched services migrate to IP networks and data grows, networks must evolve to accommodate the traffic. However, IP may need to become as complex as ATM to replace its functionality. Thus, both ATM and IP are candidates for transport directly over DWDM. In either case, the result is simplified network infrastructure, lower cost due to fewer network elements and less fiber, open interfaces, increased flexibility, and stability. The question is, in which format will IP travel over an optical network: IP over ATM over SONET, IP over SONET (as POS), or IP over Gigabit Ethernet or 10 Gigabit Ethernet? (See Figure 3-1.)

Figure 3-1 Data Link and Network Protocols over the Optical Layer



Fibre Channel

Fibre Channel is the predominant data link technology used in storage area networks (SANs). See the “Storage Area Networks” section on page 3-5. Fibre Channel is an economical replacement for the Small Computer System Interface (SCSI) protocol as a high-speed interface for applications such as data backup, recovery, and mirroring. Fibre Channel interfaces are available at 100 MBps today; 200 MBps interfaces should be available in the near future, and 400 MBps interfaces are in testing.



Note

By convention, transfer rates for storage are specified in megabytes per second (MBps).

Fibre Channel comes without the very short distance limitations of SCSI; it also avoids the termination restrictions of SCSI because each node acts as an optical repeater. Fibre Channel can be implemented in a point-to-point, arbitrated loop, or mesh topology using a switch. As shown in Figure 3-1, Fibre Channel, like other protocols, can be carried directly over the optical layer using DWDM.

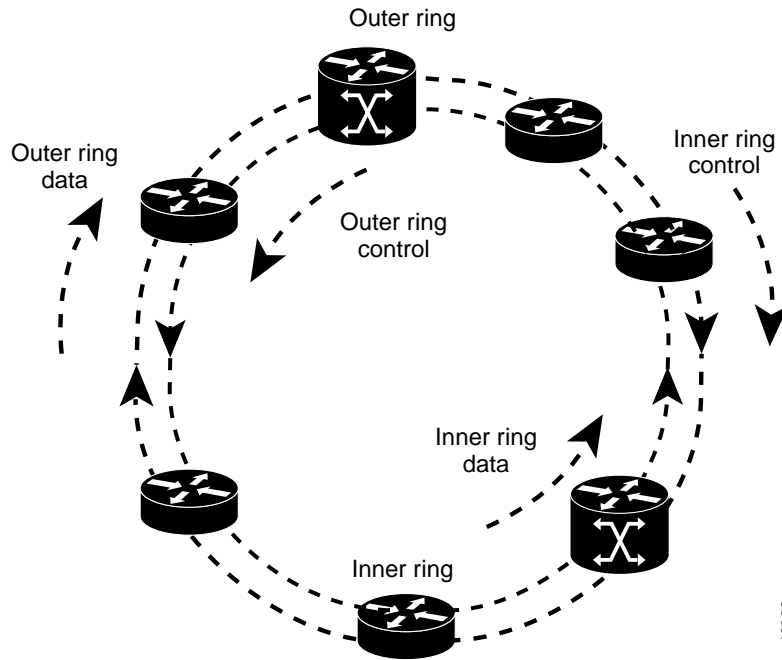
Dynamic Packet Transport

Dynamic Packet Transport (DPT) is a Cisco protocol that provides an alternative to SONET for more efficient transport of data in ring architectures. DPT supports basic packet processing, fairness, multicasting, Intelligent Protection Switching (IPS), topology discovery, Address Resolution Protocol (ARP), routing, and network management. DPT can run over dark fiber, SONET, or WDM.

DPT’s chief advantage over SONET is its ability to reuse bandwidth that would have otherwise been lost. Bandwidth is consumed only on traversed segments, and multiple nodes can transmit concurrently.

DPT is based on bidirectional counter rotating rings (see Figure 3-2). Packets are transported on both rings in concatenated payload, while control messages are carried in the opposite direction from data.

Figure 3-2 DPT Ring Architecture



FDDI

FDDI is at this point a legacy technology. Having served a need at one time, it has been replaced by more advanced technologies. Although FDDI is capable of scaling to the metropolitan area, it is also a shared media technology with a relatively low capacity by current standards. This limitation, along with falling availability of FDDI interfaces on network equipment, is causing FDDI to be replaced by Gigabit Ethernet, or ATM. Nevertheless, it is also a protocol that can be transparently transported over the optical layer using DWDM.

Support for Legacy Traffic

In spite of the disproportionate growth of data traffic versus voice, legacy traffic won't suddenly vanish. Networks must support diverse low speed connections in addition to newer, higher speed data connection. Thus DWDM must be complimented by electrical (TDM/FDM) multiplexing to ensure efficient use of lightwaves. At the same time, legacy traffic must be augmented with high-capacity data transport without impacting efficient IP transport.

For ISPs, the situation is different: All of their traffic is IP. ISPs need rapid build-out of networks and favor packet-over-lightwave or Gigabit Ethernet, rather than ATM or SONET. Other requirements of this market include load sharing strategies for resilience, leverage of dark fiber, and simpler datacom-like management.

Applications and Services in the MAN

The metropolitan network market is being driven by demand for new application services and the introduction of high speed access. Taken together, these forces are creating a bottleneck in the MAN.

New applications include e-commerce transactions, packetized voice, and streaming multimedia. New services, primarily to the enterprise, include interconnecting and consolidating data centers, transparent extension of the LAN across the MAN by connecting geographically disparate locations using wavelengths over dark fiber, a trend towards SAN architecture, the server-less office, real-time transactions backup, and high-speed disaster recovery. For service providers, new services include support for access technologies such as DSL, cable, and wireless (which still requires a land-based transport infrastructure) and wavelength leasing or wavelength-on-demand.

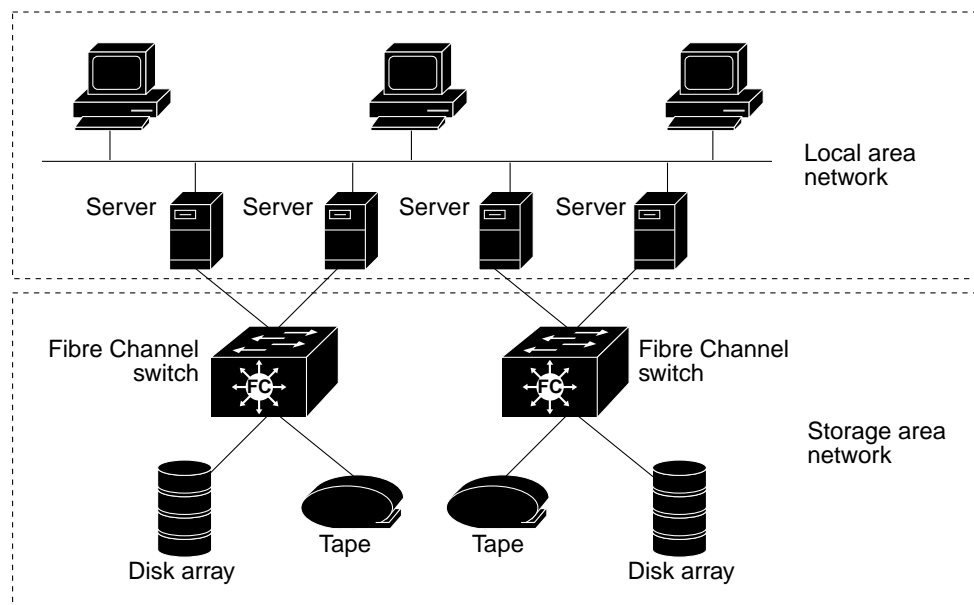
Two of the most important applications for DWDM technology in the MAN are in the areas of SANs and SONET migration.

Storage Area Networks

Storage area networks (SANs) represent the latest stage in the evolution of mass data storage for enterprises and other large institutions. In host-centric environments, storage, as well as applications, was centralized and centrally managed. With the advent of client/server environments, information that was previously centralized became distributed across the network. The management problems created by this decentralization are addressed in two principal ways: network attached storage (NAS), where storage devices are directly attached to the LAN, and SANs.

Composed of servers, storage devices (tapes, disk arrays), and network devices (multiplexers, hubs, routers, switches, and so on), a SAN constitutes an entirely separate network from the LAN (see Figure 3-3). As a separate network, the SAN can relieve bottlenecks in the LAN by providing the resources for applications such as data mirroring, transaction processing, and backup and restoration.

Figure 3-3 SAN Architecture

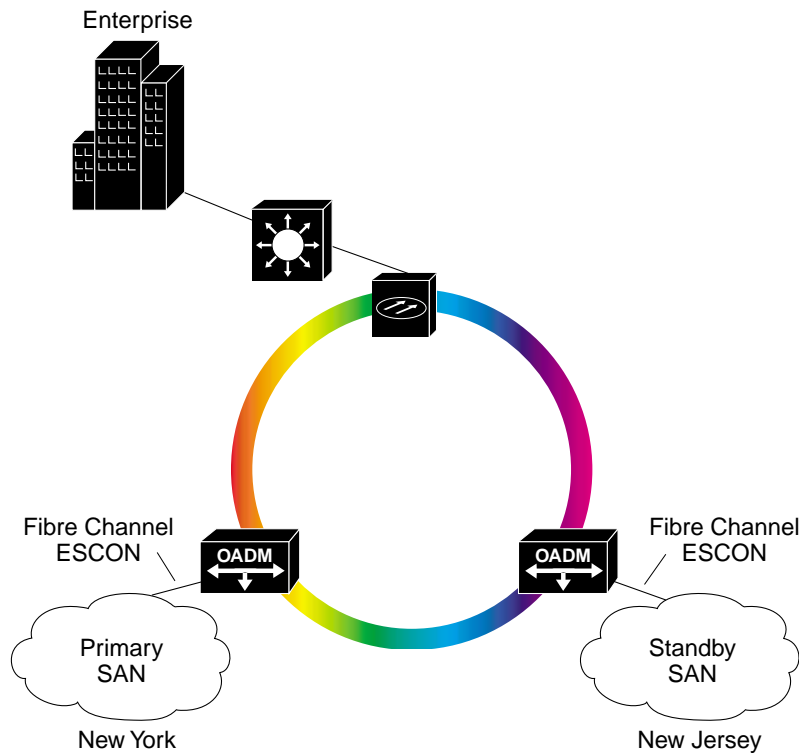


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A number of types of interfaces have been used to connect servers to devices in a SAN. The most prevalent is IBM's Enterprise System Connection (ESCON), a 17-MBps half-duplex protocol over fiber. Fibre Channel, on which IBM's FICON is based, is also frequently employed in SANs and has a much higher capacity than ESCON (see the "Fibre Channel" section on page 3-3.) Both technologies, however, have significant distance limitations. For example, the standard maximum distance without repeaters is around 3 km (1.9 mi) for half duplex ESCON and around 10 km (6.2 mi) for full duplex 100-MBps Fibre Channel. There is performance degradation as distances increase beyond these numbers.

This distance limitation can be overcome by transporting data between one or more enterprise locations and one or more SANs over the optical layer using DWDM. In Figure 3-4, for example, the distance separating the enterprise location and the SAN sites can be greatly extended. Access to the ring is by way of "satellite" OADM's with Fibre Channel or ESCON interfaces at each SAN location (one of these could provide data mirroring). These interfaces can also support Sysplex Timer and Sysplex Coupling Link interfaces, used in IBM environments for distributing loads across the members of a server complex.

Figure 3-4 SAN Access over the Optical Layer



In addition to overcoming distance limitations, DWDM can also reduce fiber requirements in SANs. Both ESCON and FICON require a pair of fibers for every channel. By multiplexing these channels over DWDM transport, significant savings can be realized.

Migration from SONET/SDH

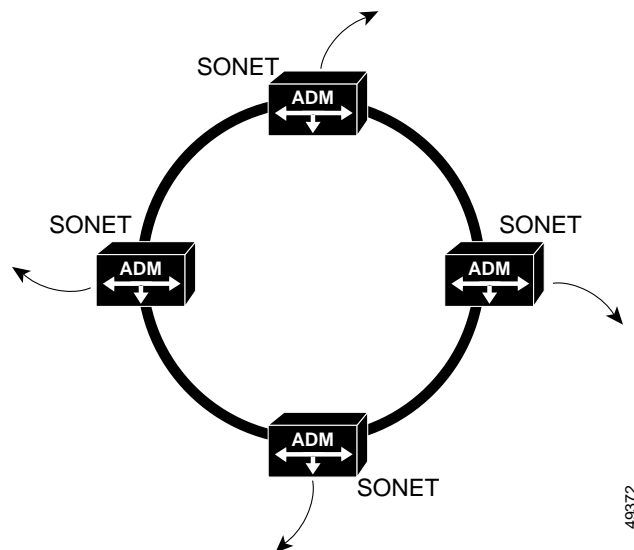
As a transport technology, SONET is an “agnostic” protocol that can transport all traffic types, while providing interoperability, protection schemes, network management, and support for a TDM hierarchy. Although SONET may continue to be the interface standard and transport protocol of choice well into the foreseeable future, upgrading it is expensive, as line-rate specific network elements are required at each point of traffic ingress or egress.

Using DWDM to increase the capacity of embedded fiber, while preserving SONET infrastructure, offers an alternative to expensive SONET upgrades. Migration from SONET to DWDM may in fact be the single most important application in the near term. In general, this migration begins by replacing backbones with DWDM, then moves toward the edges of the network.

In one common scenario, bandwidth on a SONET ring can be increased greatly by replacing SONET ADMs with DWDM equipment. In the example shown in Figure 3-5, there are three options for upgrading the ring:

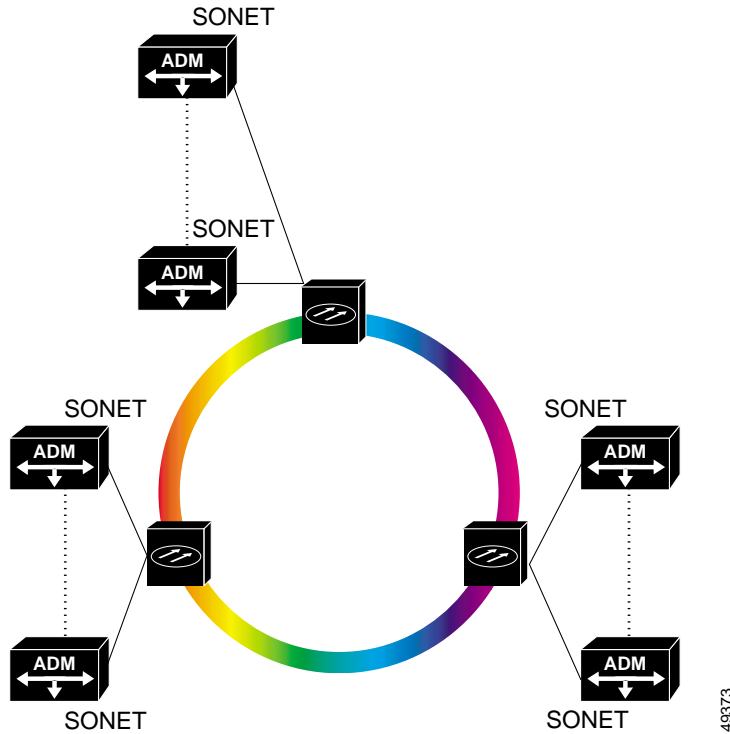
- Replace or upgrade the equipment; for example, from OC-48 to OC-192.
- Install a new ring on new or existing fiber.
- Install one or more new rings by deploying DWDM.

Figure 3-5 Migrating the SONET Ring to DWDM—Before



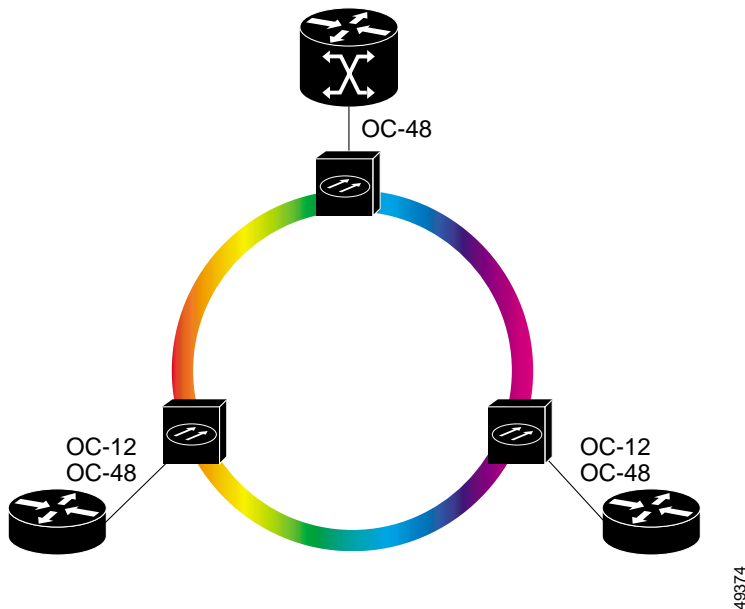
The third option is shown in Figure 3-6. By using DWDM to increase the capacity of the existing ring, one fiber can essentially act as many.

Figure 3-6 Migrating the SONET Ring to DWDM—First Stage



In a second type of scenario, DWDM can be used to remove an entire class of equipment, the SONET ADMs. This change, which might constitute a second phase of SONET migration, allows routers and other devices to bypass SONET equipment and interface directly to DWDM, while simplifying traffic from IP/ATM/SONET to POS to eventually IP directly over the optical layer (see Figure 3-7).

Figure 3-7 Migrating the SONET Ring to DWDM—Second Stage



In this phase of migration, end user sites are served by OADMs rather than SONET ADMs. In this way DWDM rings and mesh networks can eliminate the increased cost and complexity of introducing more SONET elements into the network to meet demand. The advantage here for carriers is the ability to offer bit-rate-independent services, freeing them from the DS1/DS3/OC-*n* framework. Such a scheme would also allow enterprise LAN access to be extended across the MAN or WAN without a SONET infrastructure.

A further advantage in migrating from SONET to the optical layer is that protection and restoration becomes less susceptible to failure of electronic components; a common survivability platform for all network services is created, including those without built-in protection.

Topologies and Protection Schemes for DWDM

Network architectures are based on many factors, including types of applications and protocols, distances, usage and access patterns, and legacy network topologies. In the metropolitan market, for example, point-to-point topologies might be used for connecting enterprise locations, ring topologies for connecting inter-office facilities (IOFs) and for residential access, and mesh topologies might be used for inter-POP connections and connections to the long-haul backbone. In effect, the optical layer must be capable of supporting many topologies and, because of unpredictable developments in this area, those topologies must be flexible.

Today, the main topologies in deployment are point-to-point and ring. With point-to-point links over DWDM between large enterprise sites, there needs only to be a customer premise device for converting application traffic to specific wavelengths and multiplexing. Carriers with linear-ring topologies can evolve toward full rings based on OADMs. As configurable optical cross-connects and switches become more common, these point-to-point and ring networks will be interconnected into meshes, transforming optical metropolitan networks into fully flexible platforms.

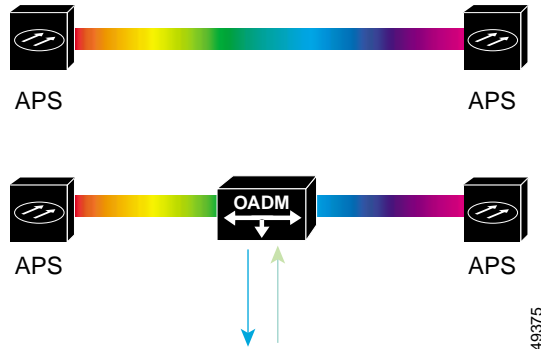
Point-to-Point Topologies

Point-to-point topologies can be implemented with or without OADM. These networks are characterized by ultra-high channel speeds (10 to 40 Gbps), high signal integrity and reliability, and fast path restoration. In long-haul networks, the distance between transmitter and receiver can be several hundred kilometers, and the number of amplifiers required between endpoints is typically less than 10. In the MAN, amplifiers are often not needed.

Protection in point-to-point topologies can be provided in a couple of ways. In first generation equipment, redundancy is at the system level. Parallel links connect redundant systems at either end. Switchover in case of failure is the responsibility of the client equipment (a switch or router, for example), while the DWDM systems themselves just provide capacity.

In second generation equipment, redundancy is at the card level. Parallel links connect single systems at either end that contain redundant transponders, multiplexers, and CPUs. Here protection has migrated to the DWDM equipment, with switching decisions under local control. One type of implementation, for example, uses a 1 + 1 protection scheme based on SONET Automatic Protection Switching (APS). See Figure 3-8.

Figure 3-8 Point-to-Point Architecture



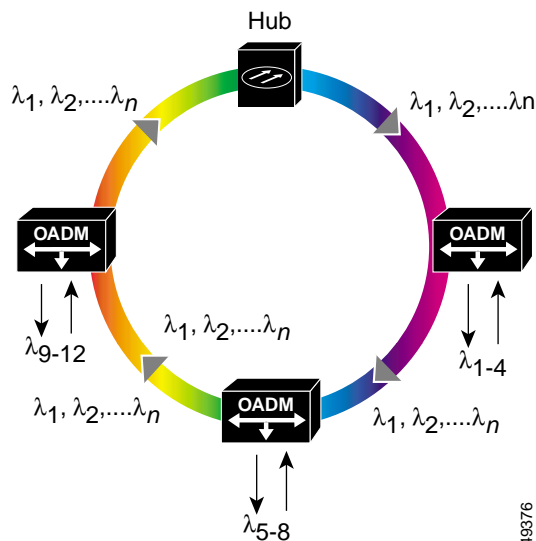
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Ring Topologies

Rings are the most common architecture found in metropolitan areas and span a few tens of kilometers. The fiber ring might contain as few as four wavelength channels, and typically fewer nodes than channels. Bit rate is in the range of 622 Mb/s to 10 Gb/s per channel.

Ring configurations can be deployed with one or more DWDM systems, supporting any-to-any traffic, or they can have a hub station and one or more OADM nodes, or satellites (see Figure 3-9). At the hub node traffic originates, is terminated and managed, and connectivity with other networks is established. At the OADM nodes, selected wavelengths are dropped and added, while the others pass through transparently (express channels). In this way, ring architectures allow nodes on the ring to provide access to network elements such as routers, switches, or servers by adding or dropping wavelength channels in the optical domain. With increase in number of OADMs, however, the signal is subject to loss and amplification can be required.

Figure 3-9 DWDM Hub and Satellite Ring Architecture

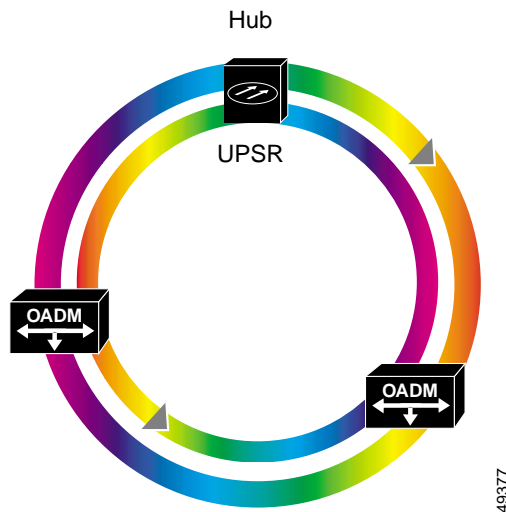


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Candidate networks for DWDM application in the metropolitan area are often already based on SONET ring structures with 1 + 1 fiber protection. Thus schemes such as Unidirectional Path Switched Ring (UPSR) or Bidirectional Line Switched Ring (BLSR) can be reused for DWDM implementations.

Figure 3-10 shows a UPSR scheme with two fibers. Here, hub and nodes send on two counter-rotating rings, but the same fiber is normally being used by all equipment to receive the signal; hence the name unidirectional. If the working ring should fail, the receiving equipment switches to the other pair. Although this provides full redundancy to the path, no bandwidth reuse is possible, as the redundant fiber must always be ready to carry the working traffic. This scheme is most commonly used in access networks.

Figure 3-10 UPSR Protection on a DWDM Ring



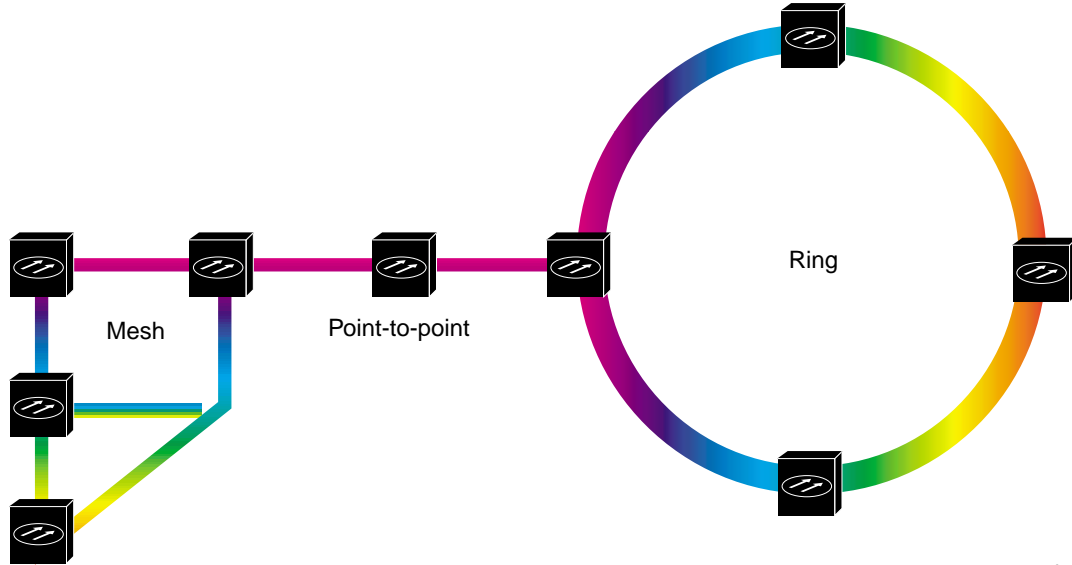
Other schemes, such as Bidirectional Line Switched Ring (BLSR), allow traffic to travel from the sending to the receiving node by the most direct route. Because of this, BLSR is considered preferable for core SONET networks, especially when implemented with four fibers, which offers complete redundancy.

Mesh Topologies

Mesh architectures are the future of optical networks. As networks evolve, rings and point-to-point architectures will still have a place, but mesh promises to be the most robust topology. This development will be enabled by the introduction of configurable optical cross-connects and switches that will in some cases replace and in other cases supplement fixed DWDM devices.

From a design standpoint, there is a graceful evolutionary path available from point-to-point to mesh topologies. By beginning with point-to-point links, equipped with OADM nodes at the outset for flexibility, and subsequently interconnecting them, the network can evolve into a mesh without a complete redesign. Additionally, mesh and ring topologies can be joined by point-to-point links (see Figure 3-11).

Figure 3-11 Mesh, Point-to-Point, and Ring Architectures



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DWDM mesh networks, consisting of interconnected all-optical nodes, will require the next generation of protection. Where previous protection schemes relied upon redundancy at the system, card, or fiber level, redundancy will now migrate to the wavelength level. This means, among other things, that a data channel might change wavelengths as it makes its way through the network, due either to routing or to a switch in wavelength because of a fault. The situation is analogous to that of a virtual circuit through an ATM cloud, which can experience changes in its virtual path identifier (VPI)/virtual channel identifier (VCI) values at switching points. In optical networks, this concept is sometimes called a *light path*.

Mesh networks will therefore require a high degree of intelligence to perform the functions of protection and bandwidth management, including fiber and wavelength switching. The benefits in flexibility and efficiency, however, are potentially great. Fiber usage, which can be low in ring solutions because of the requirement for protection fibers on each ring, can be improved in a mesh design. Protection and restoration can be based on shared paths, thereby requiring fewer fiber pairs for the same amount of traffic and not wasting unused wavelengths.

Finally, mesh networks will be highly dependent upon software for management. A protocol based on Multiprotocol Label Switching (MPLS) is under development to support routed paths through an all-optical network. In addition, network management will require an as-yet unstandardized channel to carry messages among the network elements.

Practical Considerations in Deploying DWDM

In deploying a DWDM-based network there are some considerations that will affect one's choice of vendor, equipment type, design, and so on. Some of these questions are as follows:

- Is the DWDM system compatible with existing fiber plant?

As discussed in the "Optical Fibers" section on page 2-6, some types of older fiber are not suitable for DWDM use, while newer types, such as NZ-DSF, are optimized for DWDM. Standard SM fiber (G. 652), which currently accounts for the majority of installed fiber, can support DWDM in the metropolitan area. If new fiber must be laid, a type should be chosen that will allow for future growth, particularly as DWDM systems expand into new wavelength regions and higher bit rates.

- What is my migration and provisioning strategy?

Because DWDM is capable of supporting massive growth in bandwidth demands over time without forklift upgrades, it represents a long-term investment. As discussed in the "Mesh Topologies" section on page 3-11, both point-to-point and ring topologies can serve as foundations for future growth into mesh topologies. Planning should allow for flexible additions of nodes, such as OADMs, to meet the changing demands of customers and usage.

- What network management tools can I use?

A comprehensive network management tool will be needed for provisioning, performance monitoring, fault identification and isolation, and remedial action. Such a tool should be standards-based (SNMP, for example) and be able to interoperate with the existing operating system.

- What is my strategy for protection and restoration?

Designing a protection strategy is a complex process that must take into account many variables. There are hard failures (equipment failures, such as laser or photodetector, and fiber breaks) and soft failures such as signal degradation (for example, unacceptable BER). The former must be addressed through redundancy at the device, component, or fiber level. The latter must be addressed by the system through intelligent wavelength monitoring and management. Protection and survivability strategies depend upon service type, system, and network architectures. In many networks, they also depend on the transport protocol.

Two additional and important considerations are calculation of the optical power budget and interoperability.

Optical Power Budget

Optical power budgets, or link loss budgets, are a critical part of planning an optical network. Vendors must provide guidelines, or engineering rules, to use for their equipment. In general, there are many factors that can result in optical signal loss. The most obvious of these is the distance of the fiber itself; this tends to be the most important factor in long-haul transport. In MANs, the number of access nodes, such as OADMs, is generally the most significant contributor to optical loss.

The key to precise optical power budget calculation is to get an accurate reading on the fiber using an optical time domain reflectometer (OTDR). Using an OTDR, you can obtain the following information about a span:

- Length of the fiber
- Attenuation in dB of the whole link, as well as the attenuation of separate sections of the fiber (if any)

- Attenuation characteristics of the fiber itself
- Locations of connectors, joints, and faults in the cable

The goal in calculating optical loss is to ensure that the total loss does not exceed the span budget. The following are typical values for the main elements in a span:

- Connector splice loss—This is 0.2 dB if the connectors are modern single-mode connectors from the same vendor. If the manufacturers of the two connectors (halves of the connection) are different, then the average loss is 0.35 dB.
- Fiber loss—This is about 0.25 dB/km due to attenuation.
- Fiber aging—This is about 2 dB over the life of the system.

Because optical power loss (or gain) is measured in a logarithmic value, decibels (dBs), the combined effect of all contributing elements can be calculated using simple addition. Assume a span budget of 25 dBm (a dBm is the signal power level in relation to one milliwatt), we can make the following addition:

$$\text{total system loss} + (\text{fiber length} * .25) + \text{fiber aging margin} + \text{connector/splice losses}$$

If the sum is less than 25, then we are within the span budget. If not, then some changes must be made. This might include adding an amplifier or reducing the number of loss-inducing elements on the span. Fiber conditioning, which includes resplicing fiber, connector cleaning, and so on, may also be required to reduce loss.

It is also important to ensure that the client side or tributary equipment does not overdrive the local receive laser of the DWDM equipment. This means that the client or tributary equipment must operate within the specifications of the DWDM client interface.

Although it is generally not an issue at the distances used in the MAN, remember that optical amplifiers boost the entire input, including noise. Thus over time the signal-to-noise ratio becomes so high that a clear signal can no longer be detected at the receiving end. At this point regenerators must be used to perform the 3R functions.

Interoperability Issues

Because DWDM uses specific wavelengths for transmission, the wavelengths used must be the same on either end of any given connection. Toward this end, the ITU has standardized on a grid with spacings of 100 GHz (see Table 2-1 on page 2-15). However, vendors may use wider spacing, sometimes at 200 GHz, or narrower. In addition, different vendors who do use the same grid may not use the same lambda numbering scheme. That is, lambda 1 on vendor A's equipment may be assigned a different wavelength from lambda 1 on vendor B's equipment. Hence, it is important to be aware of the potential interoperability problems posed by different grid alignments.

Other interoperability issues include power levels, inter- and intra-channel isolation, PMD tolerances, and fiber types. All these contribute to the challenges of transmission between different systems at Layer 1.

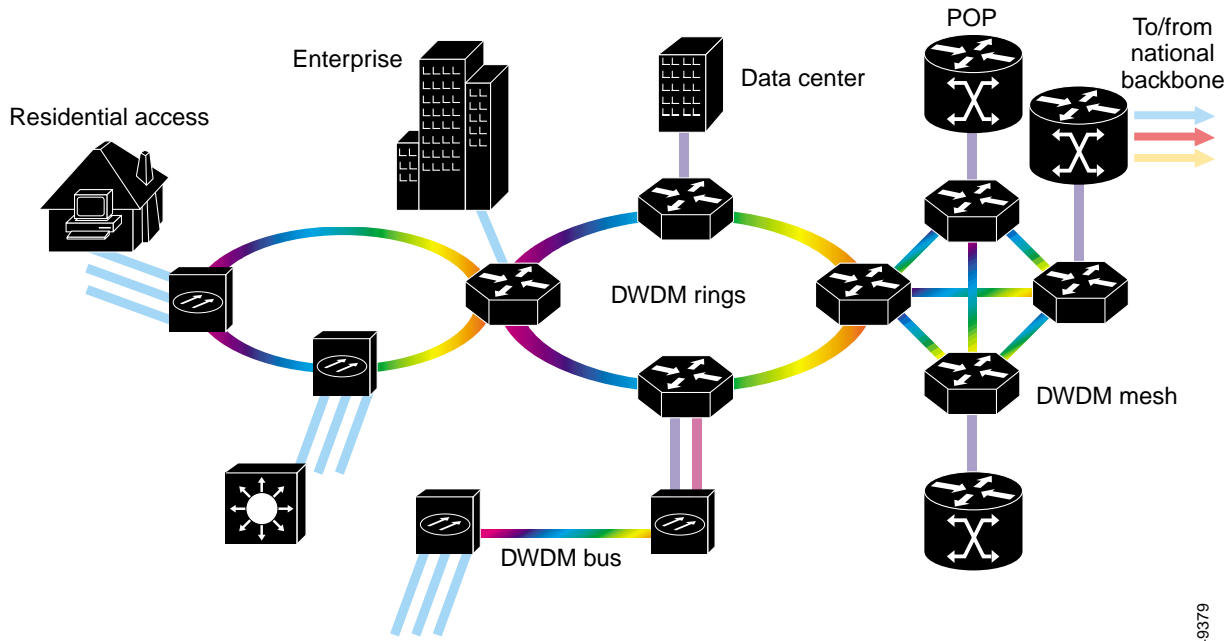
Future of DWDM

DWDM will continue to provide the bandwidth for large amounts of data. In fact, the capacity of systems will grow as technologies advance that allow closer spacing, and therefore higher numbers, of wavelengths. But DWDM is also moving beyond transport to become the basis of all-optical networking

with wavelength provisioning and mesh-based protection. Switching at the photonic layer will enable this evolution, as will the routing protocols that allow light paths to traverse the network in much the same way as virtual circuits do today.

These and other advances are converging such that an all-optical infrastructure can be envisioned. Figure 3-12 shows an example of such an infrastructure, using mesh, ring, and point-to-point topologies at the optical layer to support the needs of enterprise, metropolitan access, and metropolitan core networks.

Figure 3-12 Next Generation Metropolitan Optical Network



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