WDM TECHNOLOGIES:
OPTICAL NETWORKS
Volume III
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Dedicated to our parents,
Harish Chandra and Kalpana Rani Dutta
Debakar and Madabor Datta,
and to our families,
Keiko, Jayoshree, Jaydeep,
Sudeep Hiroshi, and Cristine Dutta
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Foreword

The WDM Revolution

These volumes are about wavelength-division multiplexing (WDM), the most recent technology innovation in optical fiber communications. In the past two decades, optical communications has totally changed the way we communicate. It is a revolution that has fundamentally transformed the core of telecommunications, its basic science, its enabling technology, and its industry. The WDM innovation represents a revolution inside the optical communications revolution, allowing the latter to continue its exponential growth.

The existence and advance of optical fiber communications is based on the invention of the laser, particularly the semiconductor junction laser, the invention of low-loss optical fibers, and related disciplines, such as integrated optics. We should never forget that it took more than 25 years from the early, pioneering ideas to the first large-scale commercial deployment of optical communications: the Northeast Corridor system linking Washington with New York in 1983 and New York with Boston in 1984. This is when the revolution got started in the marketplace, and when optical fiber communications began seriously to impact the way information is transmitted. The market demand for higher-capacity transmission was helped by the fact that computers continued to become more powerful and needed to be interconnected. This is one of the key reasons why the explosive growth of optical fiber transmission technology parallels that of computer processing and other key information technologies. These technologies have combined to meet the explosive global demand for new information services including data, Internet, and broadband services—and, most likely, their rapid advance has helped to fuel this demand. We know that this demand is continuing its strong growth because Internet traffic, even by reasonably conservative estimates, keeps doubling every year. (Today, we optical scientists and engineers puzzle over the question of why this traffic growth does not appear to be matched by a corresponding growth.
in revenue.) Another milestone in the optical communications revolution we remember with pride is the deployment of the first transatlantic fiber system, TAT8, in 1988. (Today, of course, the map of undersea systems deployed in the oceans of the globe looks like a dense spider web.) It was around this time that researchers began to explore the next step forward: optical fiber amplifiers and WDM transmission.

WDM technology has an interesting parallel in computer architecture. Computers have a similar problem as lightwave systems: both systems’ trends—pulled by demand and pushed by technology advances—show their key technological figure of merit (computer processing power in one case, and fiber transmission capacity in the other) increasing by a factor 100 or more every 10 years. However, the raw speed of the IC technologies on which computers and fiber transmission rely increases by about a factor of 10 only in the same time frame. The answer of computer designers is the use of parallel architectures. The answer of the designers of advanced lightwave systems is similar: the use of many parallel high-speed channels carried by different wavelengths. This is WDM or “dense WDM.” The use of WDM has other advantages, such as the tolerance of WDM systems of the high dispersion present in the low loss window of embedded fibers, WDM’s ability to grow the capacity incrementally, and WDM’s ability to provide great simplicity and flexibility in the network.

WDM required the development of many new enabling technologies, including broadband optical amplifiers of high-gain, integrated guided-wave wavelength filters and multiplexers, WDM laser sources such as distributed feedback (DFB) lasers providing spectral control, high-speed modulators, etc. It also required new systems and fiber techniques to compensate for fiber dispersion and to counteract nonlinear effects caused by the large optical power due to the presence of many channels in the fiber. The dispersion management techniques invented for this purpose use system designs that avoid zero dispersion locally, but provide near-zero dispersion globally.

Vigorous R&D in WDM technologies led to another milestone in the history of optical communications: the first large-scale deployment of a commercial WDM system in 1995, the deployment of the NGLN system in the long-distance network of AT&T.

In the years that followed, WDM led the explosive growth of optical communications. In early 1996, three research laboratories reported prototype transmission systems breaking through the terabit/second barrier
for the information capacity carried by a single fiber. This breakthrough launched lightwave transmission technology into the “tera era.” All three approaches used WDM techniques. Five years later, in 2001 and exactly on schedule for the growth rate of a factor of 100 per decade, a WDM research transmission experiment demonstrated a capacity of 10 Tb/s per fiber. This is an incredible capacity. Recall that, at the terabit/second rate, the hair-thin fiber can support a staggering 40 million 28-K baud data connections, or transmit 20 million digital voice telephony channels or half a million compressed digital TV channels. Even more importantly, we should recall that the dramatic increase in lightwave systems capacity has a very strong impact on lowering the cost of long-distance transmission. The Dixon–Clapp rule projects that the cost per voice channel reduces with the square root of the system’s capacity. This allows one to estimate that the preceding technology growth rate reduces the technology cost of transmitting one voice channel by a factor of 10 every 10 years. As a consequence of this trend, one finds that the distance of transmission plays a smaller and smaller role in the equation of telecom economics: an Internet user, for example, will click a Web site regardless of its geographical distance.

WDM technology is progressing at a vigorous pace. Enabled by new high-speed electronics, the potential bitrate per WDM channel has increased to 40 Gb/s and higher, broadband Raman fiber amplifiers are being employed in addition to the early erbium-doped fiber amplifiers, and there are new fibers and new techniques for broadband dispersion compensation and broadband dispersion management, etc. The dramatic decrease in transmission cost, combined with the unprecedented capacities appearing at a network node and the new traffic statistics imposed by the Internet and data transmission, has caused a rethinking of long-haul and ultralong-haul network architectures. New designs are being explored that take advantage of the fact that WDM has opened up a new dimension in networking: it has added the dimension of wavelength to the classical networking dimensions of space and time. New architectures are under exploration that are transparent to bitrate, modulation format, and protocol. Examples of this include the recent demonstrations of bitrate transparent fiber cross-connects based on photonic MEMS fabrics, arrays of micromirrors fabricated like integrated silicon integrated circuits.

Exactly because of this rapid pace of progress, these volumes will make a particularly important contribution. They will provide solid assessment
and teaching of the current state of the WDM art, serving as a valuable basis for further progress.

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Acknowledgments

Future communication networks will require total transmission capacities of few Tb/s. Such capacities could be achieved by wavelength division multiplexing (WDM). This has resulted in an increasing demand of WDM technology in communication. With increase in demand, many students and engineers are migrating from other engineering fields to this area. Based on our many years of experience, we felt that it is necessary to have a set of books that could help all engineers wishing to work or already working in this field. Covering a fast growing subject such as WDM technology is a very daunting task. This work would not have been possible without the support and help of all chapter contributors. We are indebted to our current and previous employers, NEC Research Labs, Fujitsu, Bell Laboratories, Banpil Photonics, and the University of Connecticut for providing the environment that enabled and provided the intellectual stimulation for our research and development in the field of optical communication and their applications. We are grateful to our collaborators over the years. We would also like to convey our appreciation to our colleagues with whom we have worked for many years. Thank you also to the author of our foreword, H. Kogelink, for his kindness in providing his gracious remarks in “The WDM Revolution” for our four books on WDM Technologies. Last but not least, many thanks also go to our family members for their patience and support, without which this book could not have been completed.

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Niloy K. Dutta  
Masahiko Fujiwara  

November, 2003
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1.1. Prospectus

With the recent exponential growth of Internet users and the simultaneous proliferation of new Internet protocol applications, such as Web browsing, e-commerce, Java applications, and video conferencing, there is an acute need to increase the bandwidth of the communications infrastructure worldwide. The bandwidth of the existing SONET and ATM networks is pervasively limited by electronic bottlenecks, and only recently was this limitation removed by the introduction of wavelength-division multiplexing (WDM) systems in the highest-capacity backbone links. The capacity increase realized by the first WDM systems was quickly utilized and exhausted, both fueling and accommodating the creation of new Internet services. These, in turn, are now creating a new demand for bandwidth in more distant parts of the network. The communication industries are thus at the onset of a new expansion of WDM technology, which is necessary to meet the new and unanticipated demand for bandwidth in elements of the telephony and cable TV infrastructure previously unconsidered for WDM deployment.

The growth in the transmission capacity of lightwave systems, both in laboratory experiments and in commercial systems, increased one
thousandfold from 1991 to 2001, as shown in Figure 1.1. This is only one example of the rapid increase in infrastructure brought about by the spread of the Internet. In particular, the WDM scheme is now used on trunk lines to meet the explosive increase in demand. Here, we will discuss only the transmission achieved in a multichannel WDM transmission system, which is represented by triangles and diamonds in Figure 1.1. The triangles represent laboratory results, and the diamonds show progress in commercially deployed systems. The lines are merely guides for the eye. The solid lines were drawn with the data available in 2003, whereas the dashed line has been added to include more recently reported high-capacity experiments.
The following conclusions can be drawn from the new data added to the figure (see dashed line). First, advances in the capacity of laboratory experiments since 1994, which were estimated to be growing exponentially at a rate of 4 dB per year, must be reevaluated. The current estimated rate lies nearly halfway between 2 and 4 dB per year. Second, the capacity of commercial systems seems to be growing: the gap between a laboratory demonstration and product availability has shrunk from six years in 1994 to less than two years at present.

The initial deployments of WDM were highly localized in parts of the communications infrastructure and supported by a relatively small group of experts. The new applications in different parts of the network must be implemented by a much larger group of workers from a tremendous diversity of technical backgrounds. To serve this community involved with optical networking, we introduce a series of volumes covering all WDM technologies, from optical components to networks.

Many start-ups and established companies are trying to make WDM-based products as quickly as possible to become the leader in that area. Because WDM-based products require wide knowledge, ranging from components to network architecture, it would be difficult for the engineers to grasp all the related areas quickly. Today, engineers working specifically on one area tend to be lacking in other areas, which impedes the development of WDM products. The main objective of these volumes will be to give details about WDM technology, varying from the components (all types) to network architecture. This series of volumes will be useful to graduate students and class instructors in the fields of electrical engineering, electronic engineering, and computer engineering who might also use the volumes in their courses either as textbooks or reference books.

As major developments in optical communication networks begin to capture the imagination of the computing, telecommunications, and optoelectronics industries, we expect that industry professionals will find this book useful as a well rounded reference. Through our wide industrial experience with optical networking and optical components, we know that there are many engineers who are expert in the physical layer, but who still must learn about the optical system, networks, and the corresponding engineering problems in order to design new, state-of-the-art optical networking products. These are the people for whom these books are written.
1.2. Organization and Features of the *WDM Technologies* Series

These volumes in the *WDM Technologies* series will cover everything from optical components (to be deployed or already deployed) to the network. In addition, this WDM area applies to fields from electrical engineering to computer engineering. The field itself is still evolving. This volume is not intended to include details about the basics of related topics; readers should consult the reference material, especially undergraduate-level books, for information on basic issues. What these books provide is a systematic, in-depth understanding of multidisciplinary fields for graduate students, engineers, and scientists who wish to increase their knowledge and possibly contribute to WDM technologies.

An important organizing principle of this book is that research, development, and education involving WDM technologies should allow tight coupling between network architectures and device capabilities. Research on WDM has taught us that, without sound knowledge of devices’ or components’ capabilities and limitations, one can produce architecture that is completely unrealizable. Similarly, new devices, developed without the concept of the useful system, can lead to sophisticated technology with limited or no usefulness.

These books on various areas of WDM technologies are divided into four volumes, each of which is itself divided into several parts, to provide readers and educators with a clear conception of the possibilities of their technologies in particular networks of interest. The series starts with two complete volumes on optical components. Because there are numerous chapters on related components, we decided to publish separate volumes for active and passive optical components. This format should prove more manageable and convenient to the reader. Other volumes are on optical networks and optical systems. Volume I gives an overview of WDM components, especially all kinds of active optical components [1]. Volume II, covering key passive optical components, follows [2]. Volume III deals with WDM networks and their architecture, including that which could be implemented on networks in the near future. Finally, Volume IV describes the WDM system, including a chapter on system aspects implementable in WDM equipment. All of these volumes cover not only recent technologies, but also future technologies. Each volume’s contents are explained separately in its first chapter, to accommodate readers who choose to buy just one volume. This chapter contains the survey of this volume.
1.3. **Survey of Volume III, WDM Technologies: Optical Networks**

Unlike most available textbooks on optical fiber communication, Volume III covers only optical networks. Based on our 25 years of hands-on experience in this area, we focus on those technologies that could be practically used in most WDM communication. The organization of Volume III is outlined in Figure 1.2. This book is divided into three parts:

- Part I: WDM and TDM (time-division multiplexing) Perspectives
- Part II: Critical Technologies
- Part III: Applications

Each chapter of each part is structured independently, so that interested or advanced readers can find the part/chapter of interest. The rest of this chapter gives a brief survey of the chapters of each part to show the elements of the book in context.

### 1.3.1. **PART I: WDM AND TDM PERSPECTIVES**

This part consists of this chapter, which provides a prospectus of WDM networks and an overview of this book, and Chapter 2, which provides...
extensive differentiation of the WDM and TDM for photonics networks. Chapter 2 also discusses current network applications and future directions.

1.3.1.1. Chapter 2: WDM and TDM for Photonics Networks

The information revolution was triggered mainly by the advent of optical communications. Photonic networks are beginning to take on an important role as global information infrastructures. In an optical communication network, WDM is being widely deployed by several telecommunications companies, mainly for point-to-point communication (mostly trunk lines), because it is a cost-effective alternative to laying more fibers. The highest experimental information capacity reported at OFC 2001 was 10.92 Tbit/s [3]. Alternative techniques to access the huge bandwidth for high-speed networking applications is the TDM in optical networks, leading to optical TDM (OTDM). Perspectives on both WDM and TDM for high-speed optical networks are given in Chapter 2, by H. Sotobayashi and T. Ozeki, pioneers in these networks. After reviewing current optical signal-processing technologies, the authors discuss the possibility of optical networks using both WDM and OTDM hierarchically.

1.3.2. PART II: CRITICAL TECHNOLOGIES

Some of the great advances in optical communication networks are possible not only because of advances in optical components, as described in volumes I and II, but because of the development of some critical technologies. Part II describes some critical technologies that play an active role in the success of optical networks. These chapters also discuss current network applications and future directions.

1.3.2.1. Chapter 3: Optical Path Cross-Connect

A telecommunication network can be divided into two network layers: the service network layer and the transport network layer. The service network layer consists of circuits and flows, which provide the public with switched telephone service, leased-line service, Internet service, and so on. The transport network layer consists of path networks and physical media networks, which include optical fiber and radio wave transmission systems. The path networks bridge the physical media and circuit networks.
Service networks are logical networks and are service dependent; the transport network layer, on the other hand, is less service dependent and is the platform for telecommunications networks. A path in the transport networks is a group of circuits or flows, or more generally, is a unit of network operation, design, and provision. Basic path attributes are the route, bandwidth, and QoS (quality of service).

Path technologies for realizing the different optical networks are described in Chapter 3, by K. Sato and M. Koga, pioneers in optical networks from NTT. The electrical path concept, such as SDH digital path and ATM virtual path, is extended to an optical layer by utilizing WDM technologies.

1.3.2.2. Chapter 4: Optical Packet Switching

There are many ways to route optical information over wavelengths in the networks. One of the techniques is optical packet switching. Since the major services required in communication networks today are data oriented, packet-routing technologies, especially for IP packets, are dominant. WDM technology has the potential to realize large-scale and flexible packet-switching/routing fabrics. A WDM-based optical packet switch can shift optical packets to any free wavelength in its outbound links. The probability of packet dropping can be reduced by wavelength conversion. In Chapter 4, different optical packet-switching architectures and their respective technologies are described by N. Henmi and S. Araki.

1.3.2.3. Chapter 5: Submarine Networks

A cornerstone of the optical network revolution is the submarine network, the technology that helps to increase the capacity for information. The transmission capacity of installed submarine optical cable systems increased one thousandfold from 1991 to 2001. The most prevalent submarine technology telecommunications has been the optical amplifier (described in Volume II: WDM Technologies: Passive Optical Components [2]), which has enabled many facets of today’s optical revolution for the long-haul application. Optical amplifier improvement has increased the data rate from OC 3 to OC 192 (and very soon to OC 768) and the distances from a few kilometers to thousands of kilometers. The dense WDM (DWDM) application is also possible due to advancement in submarine network technology using optical amplifiers. S. Yamamoto and T. Miyazaki of KDD highlight the
network technologies of submarine cable systems using optical amplifier technology in Chapter 5. Future submarine network architectures are also discussed.

1.3.3. PART III: APPLICATIONS: LOCAL/COMPUTER WDM NETWORKS

Recent trends in WDM application necessitate cost-effective systems and efficient architecture. Part III comprises three chapters covering three applications, from public to private networks. Distances vary from medium-to short-haul (i.e., from a few meters to a few tens of kilometers) frequently used in telecommunication. These chapters provide current network applications and future directions.

1.3.3.1. Chapter 6: WDM Networks: Metro/Access Application

T. Sugie and K. Okada have many years of experience in designing WDM systems for metro and Access applications. In Chapter 6, T. Sugie and K. Okada describe the basic concepts and design details of Metro and Access networks. Recent trends and future directions are also included in this chapter.

The main challenge of WDM technology application to Metro/Access networks is to achieve cost effectiveness and flexibility in coping with the various services required in these areas. T. Sugie and K. Okada have many years’ experience in developing optical subscriber networks in Japan. In Chapter 6, they describe how to expand network flexibility without raising costs by using WDM technologies. The chapter stresses the PON (passive optical network) and WDM rings in the network architecture.

1.3.3.2. Chapter 7: Broadcast Center Network

Video signal routing networks in television broadcasting stations have recently been undergoing a process of total digitalization. Such networks are required to handle more than 200 uncompressed serial digital video signals, whose speed is in the hundreds of Mb/s. In this regard, optical technologies have been shown to offer great promise for increasing network capacity and flexibility alike. In Chapter 7, M. Fujiwara and T. Shiozawa explain an optical network utilizing WDM technology combined with
TDM technology, designed for a television broadcast center application. In 1997, the authors’ team developed the world’s first commercial broadcast center network whose throughput could reach as high as 73Gbps. This was earlier than the rapid increase in capacity of commercial WDM transmission systems, which started around 1998.

1.3.3.3. Chapter 8: WDM Computer Networks

The major applications utilized in communication networks are data communications, such as electronic mail and database management. In this regard, the application of WDM technologies in constructing computer networks is an important issue. In Chapter 8, M. Sivakumar and K. Sivalingam give an excellent review of the application of WDM technologies to computer networks, from a local area network (LAN) to a wide area network (WAN).

References

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Part 1 Overview and WDM/TDM Perspectives
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2.1. OTDM and WDM for Large-Scale Photonic Networks as the Global Information Infrastructure

In the beginning of the 21st century, the information revolution covers the entire world. The information revolution was triggered by the advent of optical communications [1], and it is hoped that this revolution will realize a sustainable social system across the earth. Photonic networks are beginning to take on an important role as a global information infrastructure for supporting economic activities, education, and mutual understanding of people in the planet.

The transmission capacity of installed submarine optical cable systems increased one thousandfold from 1991 to 2001, as shown in Figure 2.1. This is only one example of the rapid increase in infrastructure brought about by the spread of the Internet. In particular, the wavelength-division multiplexing (WDM) scheme is now used on trunk lines to meet the explosive increase in demand for data traffic. The highest experimental information capacity reported at OFC 2001 was 10.92 Tbit/s employing Erbium-doped fiber amplifier (EDFA), gain-shifted-EDFA, and GS-TDFA, with 273 channels of 40 Gb/s transmitted over 117 km [2], where the bitrate
per bandwidth of the WDM reached 0.8 bit/s/Hz by employing polarization division multiplexing.

WDM technology is foreseen as being used in a new generation of networks, such as WDM ring networks using add-drop multiplexers (ADM) and optical path cross-connect–(OPXC) meshlike networks, as the infrastructure of the near future. The routing capability of WDM may help to realize WDM-based multiprotocol label switching (MPLS) and optical packet data switching for more economical and efficient IP networks. Comparison of optical time division multiplexing (OTDM) and WDM is an interesting issue for such networks, but the installation of OTDM or WDM is basically dominated by the issue of economical installation and harmonization with existing networks.

Hierarchical optical path architecture consisting of WDM bands and channels has been proposed as suitable for large-scale WDM
backbone networks [3]. The grouping of wavelength optical paths, that is, the wavelength-band path, is one way to reduce the complexity and size of the OPXC. In particular, hierarchical OPXC using the matrix WDM scheme is a reliable and economical high-performance node architecture [4]. This new OPXC architecture is clearly suitable for large-scale WDM backbone networks. Figure 2.2 illustrates the concept of hierarchical band structure. The great bands are located in the [upper to fiber physical layer], and each band is 40 nm wide. The great band includes smaller bands, which are groups of WDM channels. The number of WDM channels included in a band, that is, the size of aggregation, is 8 to 16; this number should be determined considering total network cost and hardware modularity [5]. The size of aggregation determines the optimal number of ports for handling network traffic. In an intranode WDM subsystem, WDM chips integrate transmitters with band-MUX, and receivers with band-DEMUXes, which increases modularity. The details of band structure should taken into account in the TMN monitoring scheme.

Fig. 2.2 Hierarchical WDM structure.
Hierarchical OPXCs have the following merits:

- OPXCs have the advantage of modularity, that is, relatively small-scale modular OPXCs make up large-scale OPXC systems. Small-scale nodes contain small numbers of channel-OPXC modules.
- The superior crosstalk specification of DEMUX becomes a serious issue in large-capacity backbone networks. It has been shown that the cascading of DEMUX filters is effective in reducing crosstalk [4].
- A large-scale optical switch network can be realized with ease.
- Network management complexity can be reduced through the use of the two-layered optical path concept [6]. The TMN information of wavelength channels is masked so that the network can be managed using the conceptual higher layers. The hierarchical WDM network architecture can realize an economical large-scale network using node cut-through of the waveband-path, as shown in Figure 2.3.

The band can also be used to transmit higher bit-rate OTDM signals, instead of a group of optical paths. This scheme has been proposed as a hybrid hierarchical OTDM/WDM network [7]. One of the aims of using OTDM in the band path is the ability to monitor the error-free transmission in the physical layer. Error-free transmission monitoring is necessary to cut through the high-level nodes. When the band-path is not used to transfer a group of WDM channels, OTDM seems to be the only way to monitor

![Hybrid hierarchical OTDM/WDM network architecture.](image-url)
error-free transmission quality by electronic means, after bit and frame synchronization. For example, OTDM has been used in conjunction with an optical sampling technique to measure average Q-value [8]. The OTDM bitrate has reached 1.28 Tbit/s by using all-optical signal processing and polarization multiplexing [9]. The third- and fourth-order chromatic dispersions were simultaneously compensated for by using a phase modulation. A 640 Gb/s full OTDM demultiplexing using a nonlinear optical loop mirror (NOLM) has also been demonstrated [10].

Figure 2.4 illustrates the node structure of proposed hybrid hierarchical OTDM/WDM networks. Realization of the hybrid hierarchical OTDM/WDM network requires further challenges in ultrafast photonic processing and femtosecond opto-electronic devices. The input WDM signals from a transmission fiber are demultiplexed by a band-DEMUX.
Firstly, each band should be checked to guarantee error-free conditions. This guarantees error-free operation of the upper nodes of the band-paths. An interferometric semiconductor switch of symmetric Mach–Zehnder (SMZ) type, operated at 160 Gb/s OTDM systems, is a basic device for all-optical signal processing, such as parity check for error detection [7]. After error-free conditions are checked, the bands are then switched according to a cross-connect program. Node cut-through bands are switched to the output band-MUX after passing through the all-optical signal processing unit, which may transform them to the new wavelength of the bands for the virtual wavelength band-path scheme. The other bands are switched to drop ports. The size of this space switch is remarkably small compared to that of WDM-channel OPXC. The dropped bands are then deassembled to WDM channels to feed channel-based OPXCs. IP-routers and ATM-switches process the packet-based routing and switching and forward the packets to individual, channel-based OPXC. The output channels are assembled, or aggregated, into bands by channel-to-band converters, which employ various kinds of ultrafast photonic processing.

An important issue regarding hierarchical hybrid OTDM/WDM network nodes is how to realize ultrafast photonic processing, aiming for efficient and economical node realization. The functions desirable to be realized by all-optical means are listed below:

- Format conversion (mutual conversion between OTDM and WDM)
- OTDM/WDM wavelength conversion
- Equalization of dispersions
- Improvement of spectral efficiency
- Error monitoring for node cut-through

Section 2.2 discusses ultrafast photonic processing, especially supercontinuum (SC) technology. Section 2.3 describes wavelength-band generation and Section 2.4 discusses all-optical OTDM/WDM mutual format conversion. In Section 2.5, wavelength-band conversion is examined, and in Section 2.6, polarization-mode dispersion equalization is discussed. Finally, discussions are concluded in Section 2.7.

### 2.2. Ultrafast Photonic Processing

Ultrafast photonic processing techniques are expected to play a major role in future photonic networks. At data rates of 40 Gb/s or above, electronics
imposes severe technological and economic constraints that ultrafast photonic processing could advantageously remove. The quasi-instantaneous response of Kerr nonlinearity in fibers makes photonic processing a most attractive effect to overcome bandwidth limitations. Consider two optical beams of different wavelengths co-propagating in the same fiber, as shown in Figure 2.5. The intensity dependence of the refractive index leads to a large number of interesting nonlinear effects: self-phase modulation (SPM), cross-phase modulation (XPM), and four-wave mixing (FWM) [11].

Photonic processing using optical fiber nonlinearity can be categorized into three functions, as shown in Figure 2.6. One is optical multiplexing, which is used in optical switches, multiplexers, and demultiplexers. The second is wavelength conversion, which is used in a variety of WDM systems. The third is phase-conjugation generation, which is used in the midway optical phase conjugation (OPC) system.

\[
E(t) = E_0(t) \exp(-i\omega_0t) + E_1(t) \exp(-i\omega_1t)
\]

\[
i\gamma |E|^2 E = i\gamma \left( |E_0|^2 + 2|E_1|^2 \right) E_0 \exp(-i\omega_0t) + i\gamma \left( 2|E_0|^2 + |E_1|^2 \right) E_1 \exp(-i\omega_1t) + i\gamma E_0^2 E_1^* \exp(-i[2\omega_0 - \omega_1]t) + i\gamma E_0^* E_1^2 \exp(-i[-\omega_0 + 2\omega_1]t)
\]

**Fig. 2.5** Nonlinear effects in an optical fiber.
One of the applications of photonic processing using optical fiber nonlinearity is supercontinuum (SC) generation. SC generation is a promising technique for generating a multiwavelength optical source, used mainly for WDM networks. SC can be generated by spectrum broadening through pulse compression in the time domain, using soliton effects in an anomalous dispersion regime [12, 13], or by spectrum-broadening through the accumulation of frequency chirping caused by optical Kerr effects in the normal dispersion regime [14, 15]. In the latter case, the output SC pulse is a single pulse with a rectangular shape in the time domain, and its frequency chirping is a linear up-chirp.

Figure 2.7(a) shows the operating principle of the conventional wavelength tuning method, which uses spectrum slicing [12–15]. When the center wavelength of spectrum slicing is controlled, the center wavelength of the spectrum-sliced SC pulse can be tuned. The output pulse filtered out from the SC is always a single pulse. The normal dispersion is also useful for generating a spectrum with less intensity fluctuation. Increasing the input peak power can generate a wider spectrum. These characteristics are attractive for the application of wavelength-tunable light sources. However, the spectrum-slicing method only generates the same data sequence with the data sequence of SC pulse.
Fig. 2.7 Operating principle of tunable wavelength conversion by (a) spectrum-slicing and (b) time-gating of a highly chirped, rectangular SC pulse.

Figure 2.7(b) shows the operating principle of the time-gating method [16]. Because SC pulses generated by nonlinear propagation in normal dispersion fiber are rectangular pulses with linear up-chirping, shifting the position of the time-gating allows tuning of the center wavelength of time-gated SC pulses. As for data sequence mapping, when data 1 or 0, respectively, opens or closes the time-gate window, the time-gated SC pulses possess the same data sequence as the time-gating data sequence. When 10 Gb/s RZ data sequences of wavelength $\lambda_0$ are used for
controlling the time-gating ON/OFF window of optical time-gating, the time-gated SC pulses become wavelength-converted 10 Gb/s RZ data sequences. This is because the center wavelength of the time-gated SC is different, corresponding to its time-gating position, as shown in Figure 2.7(b). In conventional wavelength conversion methods, such as four-wave mixing (FWM) based wavelength conversion, if the wavelength to be converted changes, the wavelength of the pump source must be tuned, which is a complex operation. In the proposed time-gating method, wavelength tuning can be done only by shifting the time position of control pulse, resulting in a simple operation.

Another advantage of the time-gating method is that the wavelength can be tuned by controlling the pump power of the SC fiber (SCF). Because the amount of frequency chirping depends on the pump pulse power of the SCF, the wavelength-tuning range and the center wavelength of the time-gated SC pulse can be tuned simply by changing the pump pulse power to SCF. In comparison with FWM wavelength conversion, which needs a wide wavelength tunable pump source, the proposed method can easily change the entire tuning range.

Figure 2.8 shows the experimental setup for tunable wavelength conversion by optical time-gating of SC. To generate highly linearly chirped, wide, and rectangular SC pulses, a 10 GHz repetition rate and 1.5 ps width pulse trains at 1550.0 nm from the mode-locked laser diode (MLLD) [17, 18] are used. After being amplified by an EDFA to the average power of $P_{in}$, the pulses are launched into 2-km long SCF [14]. A 3.5-km dispersion-shifted fiber with the normal dispersion is used for further time-stretching. For the pump data sequence to a saturable absorber (SA), 10 GHz repetition

![Diagram of experimental setup](image-url)

**Fig. 2.8** Experimental setup of tunable wavelength conversion by optical time-gating of a highly chirped, rectangular SC pulse.
rate, 1560 nm ($= \lambda_0$), 5.0 ps pulse width mode-locked fiber laser (MLFL) pulses are modulated with a 10 Gb/s PRBS of $2^{23} - 1$.

The optical time-gating device is a semiconductor SA with a bias voltage of $-1.7$ V [17, 18]. The 10 GHz SC pulses are optical time-gated in the SA, which is pumped by 10 Gb/s RZ data signals of $\lambda_0$. The SA opens and closes the time gates to the SC pulse when the high-power data 1 and the no-power data 0 are used as pump pulses, respectively, because only high-power pulses saturate the absorption. The duration of the time window is 6.5 ps. The average power of the input pump pulse signal is 24 dBm. The time position of optical time-gating is aligned with an optical delay line with 10 fs accuracy. The center wavelength of time-gated SC pulses differs according to the time position of the time-gating. The optical spectra and bit error rates (BERs) of the wavelength-converted RZ signals are measured using an optical spectrum analyzer and a 30 GHz photodetector (PD) with a BER tester (BERT).

The measured optical spectra are shown in Figure 2.9(a). When the input powers to SCF ($P_{in}$) are 60 mW, 125 mW, and 200 mW, the 3 dB spectrum widths are 10.1 nm, 20.0 nm, and 30.2 nm, respectively. In each case, pulse shapes are almost rectangular and pulse widths of the full width at half maximum are 100 ps, 103 ps, and 105 ps, respectively, and the time-band width products are 131.3, 257.5, and 396.4, respectively. These results show that generated SC pulse is highly chirped and the amount of chirping can be easily controlled by changing the input power to SCF.

Figure 2.9(b) shows the center wavelength of the time-gated SC pulse plotted versus the time-gating position. By shifting the time-gating position, the converted wavelength can be precisely tuned almost linearly. Furthermore, by changing the input power to SCF, resulting in an SC spectrum-width change, the tuning range can be easily controlled. The entire tuning ranges are 9.0 nm, 18.9 nm, and 27.1 nm for $P_{in}$ of 60 mW, 125 mW, and 200 mW, respectively. The pulse widths of the wavelength-converted signals are about 6.5 ps. Because the SC pulse before time-gating is linearly up-chirped and the SA-induced chirping is small [17, 18], the wavelength-converted signals are considered to be almost linearly up-chirped. With the proper amount of linear chirping compensation accompanied by optical filtering, the wavelength-converted signals can be almost transform-limited.

Figure 2.9(c) shows the measured BERs when $P_{in}$ is 200 mW. All BERs are at the converted wavelengths of 1537 nm, 1550 nm, and 1563 nm,
which correspond to the relative time-gating positions of 95 ps, 50 ps, and 5 ps, respectively, in a 100 ps repetition time frame, and are below $10^{-9}$. The power penalties of about 4 dB are mainly due to pulse-width changes in the wavelength conversion, amplified spontaneous emission noise in the EDFA allocated before SCF, and 7 dB insertion loss of SA in the open time frame. As can be estimated in Figure 2.9(b), using the delay line with 10 fs accuracy, the minimum wavelength tuning resolution can be estimated to be 0.03 nm, because the center wavelength of the time-gated signals is almost linearly controlled by the time-gating position.

In this section, as one application of ultrafast photonic processing, we have proposed a novel wavelength conversion technique of RZ data
sequences. Precise tuning can be done over a wide and variable tuning range. The proposed method has been realized by adjusting the time-position of the optical time-gating of highly chirped rectangular SC pulses. Error-free 10 Gb/s wavelength conversion with the tuning range of 27.1 nm has been demonstrated experimentally. The proposed method offers a powerful tool for developing ultrafast photonic networks.

2.3. Wavelength-Band Generation

To meet the rapid increase in the demand for multiterabit/s transmission capacities, 40 Gb/s-based dense wavelength division multiplexing (DWDM) is becoming the next generation in large-capacity systems. Expansion of WDM channels results in an increase in the complexity of optical network node. As described in Section 2.1, the hierarchical structure suggests a natural method of wavelength-band routing to achieve a high degree of spectrum reuse [3]. In such networks, wavelength-band generation will be a key technology [19].

Forty Gb/s-based multiterabit/s DWDM systems have several problems to be overcome. These problems include wavelength dispersion, dispersion slope, polarization-mode dispersion, and nonlinear effects of the transmission line. Other critical issues are the linear and nonlinear crosstalk from adjacent channels and the cost increase of the WDM signal control. The adjacent channel crosstalk problem can be solved by using the carrier-suppressed return-to-zero (CS-RZ) modulation format, which is one of the promising signal formats that exhibits lower spectrum bandwidth than the conventional RZ format and good tolerance to nonlinear effects [20, 21]. To reduce the total cost of signal sources and their center wavelength stabilization, multicarrier generation from a single SC source has been proposed [22].

This section describes a simple configuration for a frequency-standardized, simultaneous wavelength-band generation method in CS-RZ format that uses a single SC source, which is directly pumped by an optically multiplexed CS-RZ signal. Transmission of simultaneously generated 3.24 Tbit/s (81 WDM × 40 Gb/s) CS-RZ over an 80 km dispersion compensated link has been experimentally demonstrated using tellurite-based, erbium-doped fiber amplifiers (T-EDFAs) with a 66-nm continuous signal band in the C- and L-bands.
2.3.1. OPERATING PRINCIPLE OF SIMULTANEOUS WAVELENGTH-BAND GENERATION OF FREQUENCY-STANDARDIZED DWDM IN CS-RZ FORMAT

Unlike the conventional 40 Gb/s CS-RZ generation, which uses a complex ETDM setup [20, 21], we generate 40 Gb/s CS-RZ using a simple optical multiplexer integrated as a planar lightwave circuit (PLC), as shown in Figure 2.10(a). A 10 Gb/s RZ signal is optically time-delayed multiplexed into a 40 Gb/s signal. The optical carrier phase of each delayed adjacent pulse is shifted by $\pi$, using optical phase shifters in the time domain. As a result, 40 Gb/s CS-RZ format multiplexing is obtained.

Simultaneous multiwavelength 40 Gb/s CS-RZ multiplications are performed by SC generation directly pumped by a 40 Gb/s CS-RZ signal. Because SC is generated by frequency chirping accumulation by the nonlinear propagation in a normal dispersion fiber [14], no coherent degradation occurs and the relative phase between the adjacent pulses is conserved [23, 24]. By spectrum slicing of SC using an arrayed waveguide grating (AWG), simultaneous multiwavelength SC-RZ can be generated, as shown in Figure 2.10(b). The merit of this method is its great ease of WDM channel spacing control. The channel spacing is strictly locked by the microwave mode-locking frequency of the source laser [22]. It is not necessary to control the center wavelength of each WDM channel. Thus, the frequency-standardized wavelength-band of DWDM in SC-RZ format is generated by a simplified method of SC generation, which is directly pumped by a single optically multiplexed CS-RZ format signal [19].

2.3.2. EXPERIMENTS AND RESULTS

Figure 2.11 shows the experimental setup for simultaneous generation and transmission of a 3.24 Tbit/s (81 WDM × 40 Gb/s) wavelength-band in CS-RZ format. Ten GHz, 1.5 ps pulse trains from the MLLD of 1530.33 nm were modulated with a 10 Gb/s PRBS of $2^7 - 1$ and optically multiplexed into 40 Gb/s CS-RZ format by using time-delayed optical multiplexer with phase shifter, as shown in Figure 2.10(a). After being amplified to an average power of 1.2 W, the multiplexed signal was launched into the SCF. The SCF was a 2-km long dispersion flattened fiber with a small normal dispersion value [14]. The spectrum of 40 Gb/s CS-RZ signal
Fig. 2.10 Operating principle of (a) CS-RZ generation in the optical domain using a time-delayed optical multiplexer with phase shifter, and (b) simultaneous wavelength-band generation of frequency-standardized DWDM of CS-RZ format using SC generation and spectrum slicing.
was dramatically broadened while maintaining its coherent characteristics. The generated 40 Gb/s CS-RZ-induced SC signal was spectrum sliced and recombined by AWGs with a 100 GHz channel spacing to generate multiwavelength 40 Gb/s CS-RZ signals, which correspond to a 0.4 bit/s/Hz spectrum efficiency. After WDM multiplexing, frequency chirping is compensated by a 13.5 m SMF, because the SC pulse was up-chirped [14]. T-EDFAs with three-stage amplification were used for amplification of the continuous signal band in the C- and L-bands [25]. Power equalization of WDM channels was done by adjusting the three stage pump powers.

Compared with a multiband repeater using separate C- and L-band amplifiers [26], a continuous signal band repeater has certain advantages, such as its simple configuration, low noise, high output power, and low cost. The transmission line was two pairs of a single-mode dispersion fiber (SMF) and a reversed dispersion fiber (RDF). The total length was 80 km, the average zero dispersion wavelength was 1546.59 nm, and the dispersion slope was 0.0087 ps/nm/km/nm. After being amplified by a T-EDFA, it was wavelength-demultiplexed by a 100 GHz spacing, 81 channels of AWG (channel 1: 1535.04 nm to channel 81: 1600.60 nm). Then, the resulting WDM DEMUX 40 Gb/s CS-RZ signal was optically TDM demultiplexed into 10 Gb/s by using a symmetric Mach–Zehnder (SMZ) all-optical switch [27]. The BERs were measured with an optical preamplified receiver and BERT.
Figure 2.12 shows the optical spectra of SC at the output of SCF (upper trace), signals before transmission (middle trace), and signals after transmission and amplified by a T-EDFA (lower trace). The $-20$ dB bandwidth of the SC spectrum was about 170 nm. The power difference in all WDM channels after 80 km transmission and amplified by a T-EDFA was about 7 dB.

In order to verify the conservation of the relative phase of $\pi$ between the adjacent pulses in the time domain, another time-delayed multiplexer with a phase shifter was used as a correlator [24], as shown in Figure 2.13(a). Input pulses were divided into two, one of which was time-delayed by 25 ps and phase shifted by $\pi$. The divided pulses were combined at the output.
When input pulse trains were 4 pulses of 40 GHz repetition rate CS-RZ format, (i.e., the pulse separation was 25 ps and relative phase between the adjacent pulses was $\pi$) output pulse trains became five pulses long with a power ratio of (1:4:4:4:1) [24]. Figures 2.13(b) through Figure 2.13(d), respectively, show the measured correlation output of the WDM channel signals of channel 1, channel 41, and channel 81 before transmission. In each WDM channel, the power ratio of the pulses was observed to be (1:4:4:4:1). It is clearly shown in the time domain that the relative phase between the adjacent pulses of $\pi$ is conserved even after simultaneous multiwavelength generation by SC generation and spectrum slicing.

Figures 2.14(a) through 2.14(c) respectively show the measured optical spectra after 80 km transmission and WDM demultiplexing of channel 1, channel 41, and channel 81. It is clearly shown in the frequency domain that optical carriers were suppressed even after 80 km transmission. Figures 2.14(d) through 2.14(f) respectively show the measured eye diagrams of WDM channel 1, channel 41, and channel 81. Eye diagrams in each WDM channel indicate good eye opening. Figure 2.15(a) shows the
Fig. 2.14 Measured optical spectra after 80 km transmission and WDM DEMUX of (a) channel 1, (b) channel 41, and (c) channel 81. Also, measured eye diagrams of (d) channel 1, (e) channel 41, and (f) channel 81.
measured BERs of 81 WDM channels after transmission. For all measured channels, the BERs were less than $1 \times 10^{-9}$. Figure 2.15(b) shows the receiver sensitivity of all 81 channels at BER of $1 \times 10^{-9}$. The strong difference in sensitivity is due mainly to differences in the WDM channel power and the wavelength dispersion of the link.

2.3.3. SUMMARY OF SECTION 2.3

We have described simultaneous wavelength-band generation of CS-RZ format by SC generation, which is pumped directly with optically multiplexed CS-RZ signals. Signal transmission of 3.24 Tbit/s (81 WDM × 40 Gb/s) CS-RZ format over 80 km with a 66-nm continuous signal band has been demonstrated at BER of less than $1 \times 10^{-9}$ with 0.4 bit/s/Hz spectral efficiency. In the proposed scheme, the channel spacing is strictly determined by microwave mode-locking frequency of the MLLD, resulting in simultaneous frequency standardization of all DWDM channels. As a result, this scheme is propitiously suitable for wavelength-band generation in hierarchical WDM networks [3, 7]. Furthermore, because this method is based purely on ultrafast photonic processing, both in the time domain and in the frequency domain, it is suitable even for a much higher channel data rate-based WDM system, regardless of the speed limitations of electrical circuits.
2.4. Format Conversion

In hierarchical hybrid networks using WDM and OTDM, multiplexing format conversion of OTDM to WDM and reconversion of WDM to OTDM will be a key technology. Conversions between OTDM and WDM have been demonstrated by using a cross-gain compression of a semiconductor optical amplifier [28] and SC generation [29, 30].

This section describes an efficient scheme of photonic multiplexing format conversion and reconversion of OTDM and WDM by wavelength interchange using optical time-gating of highly chirped SC and high-speed pulse trains. A 40 Gb/s OTDM to \(4 \times 10\) Gb/s WDM to 40 Gb/s OTDM conversion in series is experimentally demonstrated.

2.4.1. OPERATING PRINCIPLE

OTDM-to-WDM conversion is done by optical time-gating of the highly chirped SC pulse, as described in Section 2.2. The SC pulse after nonlinear propagation in normal dispersion fiber becomes almost rectangular in pulse shape and its frequency chirping is almost linear up-chirping, as shown in Figure 2.16(a). Consequently, by shifting the time position of the optical time-gating, the center wavelength of the time-gated SC pulse can be tuned. As shown in Figure 16(a), when 40 Gb/s OTDM signals are used to control the time-gating ON/OFF window of the SA, the 10 GHz repetition rate SC pulses are converted to \(4 \times 10\) Gb/s WDM signals, because the center wavelengths of four WDM channels depend on the time-gating position.

WDM-to-OTDM conversion is achieved by using the SA pumped by WDM signals. As shown in Figure 2.16(b), four time-aligned 10 Gb/s WDM signals are used for controlling the time-gating ON/OFF window of the SA; 40 GHz repetition rate pulse trains are converted to \(4 \times 10\) Gb/s OTDM signals.

2.4.2. EXPERIMENTS AND DISCUSSIONS

Figure 2.17 shows the experimental setup. A 10 GHz repetition rate optical pulse train from the MLLD [16, 17], the center wavelength, and the FWHM pulse width (which are 1548.3 nm (\(\lambda_0\)) and 1.5 ps, respectively) is divided in three. These three divided pulse trains are used as the OTDM source for
Fig. 2.16 Operating principle of (a) the photonic conversion of OTDM to WDM and (b) the photonic conversion of WDM to OTDM using optical time-gating.
OTDM-to-WDM conversion, the pump pulse for SC generation, and the signal source for WDM-to-OTDM conversion.

For OTDM-to-WDM conversion, 40 Gb/s OTDM data are generated by a four times time-delayed optical multiplexer after the 10 GHz MLLD pulses are modulated with a 10 Gb/s PRBS of $2^{23} - 1$. To generate a highly chirped, wide, rectangular pulse, 10 GHz MLLD pulses are amplified by an EDFA to the average power of 14 dBm and launched into SC fiber (SCF). SCF is a 2-km dispersion flattened normal dispersion fiber [14]. A 3.5-km dispersion shifted fiber (DSF) with the normal dispersion is used for further time-stretching. Ten GHz SC pulses are optically time-gated in semiconductor SA, with a bias voltage of $-1.7$ V [16, 17] pumped by amplified 40 Gb/s OTDM data. The time window opens while the pump pulse saturates the absorber, and its duration is 10 ps. The center wavelengths of time-gated SC pulses depend on the time position of time-gating, as explained in Section 2.2. Then, time-gated SC pulses are WDM demultiplexed using an AWG with channel spacing of 350 GHz ($\lambda_1: 1544.1$ nm–$\lambda_4: 1552.5$ nm), and an FWHM channel width of 284 GHz.
The BER of each converted WDM channel is measured with an optical preamplified receiver and BERT.

For WDM-to-OTDM conversion, $4 \times 10$ Gb/s WDM data are WDM multiplexed using the same AWG. After being amplified by a gain-flattened EDFA to the average power of 24 dBm, four WDM data are launched into the SA as the pump source for the optical time-gating. The 40 GHz pulse trains, which are generated by a four times time-delayed optical multiplexer from 10 GHz MLLD pulse trains, are optically time-gated by using the 40 Gb/s WDM data. The converted 40 Gb/s OTDM data are timedemultiplexed into 10 Gb/s by optical time-gating. The optical time-gating is done using an SA, which is pumped by 10 GHz, 2 ps MLLD at 1560 nm. The BER of each converted OTDM channel is measured with an optical preamplified receiver and BERT.

To begin the OTDM-to-WDM conversion at the point indicated in Figure 2.17, the measured optical spectrum and the corresponding temporal waveform of 40 Gb/s OTDM are shown in Figure 2.18(a) and Figure 2.18(b), respectively. Figures 2.18(c) and 2.18(d) show the converted $4 \times 10$ Gb/s WDM signals measured after optical time-gating of the SC pulses at the output of WDM MUX. Next, the WDM-to-OTDM reconversion is performed in series, and the experimental results measured at the output of the second SA are shown in Figures 2.18(e) and 2.18(f). Forty Gb/s OTDM at $\lambda_0$ is converted to 10 Gb/s WDM channels at $\lambda_1$–$\lambda_4$ and reconverted to a 40 Gb/s OTDM at $\lambda_0$ with clear eye opening. The measured BERs of the back-to-back, converted four-channel 10 Gb/s WDM and reconverted four-channel 10 Gb/s OTDM data are shown in Figure 2.19. These results show that the photonic conversion and reconversion of 40 Gb/s OTDM to WDM to OTDM are possible according to the proposed scheme.

**2.4.3. SUMMARY OF SECTION 2.4**

We have proposed a novel, bidirectional photonic multiplexing format conversion scheme between OTDM and WDM by wavelength interchange using optical time-gating of highly chirped SC and high-speed pulse trains. Photonic conversion and reconversion of 40 Gb/s ($4 \times 10$ Gb/s) OTDM to WDM to OTDM have been successfully demonstrated experimentally. This scheme is promising for future hybrid hierarchical OTDM/WDM networks.
Fig. 2.18  Experimental results of (a) optical spectrum and (b) eye diagram of input 40 Gb/s OTDM, (c) optical spectrum and (d) eye diagram of converted $4 \times 10$ Gb/s WDM, and (e) optical spectrum and (f) eye diagram of reconverted 40 Gb/s OTDM.
2.5. Wavelength-Band Conversion

In hybrid hierarchical OTDM/WDM networks, as shown in Figure 2.20, after grouping WDM channels as wavelength-band, the high-level traffic should be converted to terabit/s OTDM, which is cut through the low-level nodes with a guarantee for error-free transmission using single optical-carrier signal monitoring. The hierarchical structure suggests a natural method for using wavelength-band routing. In such cases, wavelength-band conversions and multiplexing format conversions will be key technologies. Watanabe et al. have demonstrated interwavelength-band conversions of 32 WDM $\times$ 10 Gb/s [31].

In this section, interwavelength-band conversions of 640 Gb/s OTDM signals both from C-to-L-band and from L-to-C-band, followed by 640-to-10 Gb/s OTDM DEMUX, are experimentally demonstrated based on transparent and ultrafast photonic processing [32].
2. OTDM and WDM for Large-Scale Photonic Networks

Fig. 2.20 Layered structure of a hierarchical hybrid OTDM/WDM network.

2.5.1. HNL-DSF WAVELENGTH CONVERTER

A highly nonlinear dispersion-shifted fiber (HNL-DSF) [33] was used as a wavelength converter. Figure 2.21 shows group delay and wavelength dispersion of HNL-DSF #1 and HNL-DSF #2. HNL-DSF #1 for wavelength-band conversion has the following characteristics: the zero dispersion wavelength is 1564.8 nm, dispersion slope is 0.032 ps/nm$^2$/km, the nonlinear coefficient is 15 W$^{-1}$ km$^{-1}$, and the fiber length is 100 m.

The dependence of conversion efficiency on wavelength detuning was measured using two wavelength-tunable CW lasers. For phase matching, the pump wavelength $\lambda_p$ was set to 1565.0 nm. The pump power $P_p$ was set to 24 dBm. To eliminate the influence of stimulated Brillouin scattering, the pump was frequency-modulated by a 1 MHz sinusoidal signal. The signal wavelength $\lambda_s$ was tuned from 1535 nm to 1595 nm, and the signal power was −5 dBm. The polarization states of pump and signal were...
adjusted to obtain the highest conversion efficiency. Figure 2.22 shows the conversion efficiency dependency on wavelength detuning ($\lambda_s - \lambda_p$). The highest conversion efficiency was $-14.6$ dB, including the insertion loss of 2.1 dB, and the 3 dB bandwidth was 48 nm (1540 nm to 1588 nm).

2.5.2. ULTRAFAST 640-TO-10 GB/S OTDM DEMUX

For ultrafast DEMUX using an NOLM, the walk-off between the signal and control pulses causes a serious problem. Consequently, the ultrafast NOLM should be shortened, and the wavelength dispersion and the dispersion slope of the NOLM fiber should be as low as possible. By using an HNL-DSF, which has a high nonlinear coefficient and a low dispersion slope, the walk-off problem can be overcome [34, 35]. As shown in Figure 2.23, HNL-DSF #2, used as the NOLM, has the following characteristics: the zero dispersion wavelength is 1561.1 nm, dispersion slope is 0.032 ps/nm$^2$/km, the nonlinear coefficient is 15 W$^{-1}$ km$^{-1}$, and the fiber length is 100 m.
In the following experiments, for DEMUX of a C-band (centered at 1550 nm) 640 Gb/s OTDM signal, the center wavelength of the control pulse was set to 1580 nm. As for L-band 640 Gb/s DEMUX, the same wavelength allocation was used, that is, the signal and control wavelengths were 1580 nm and 1550 nm, respectively. In both cases, the walk-off between the signal and control pulses was 100 fs. Considering that the time frame of a 640 Gb/s OTDM signal is 1.56 ps, a 640 Gb/s-to-10 Gb/s OTDM DEMUX can be obtained by using a subpico-second control pulse.

2.5.3. C-TO-L WAVELENGTH-BAND CONVERSION OF A 640 GB/S OTDM SIGNAL

Figure 2.23 shows the experimental setup of C-to-L-wavelength-band conversion of a 640 Gb/s OTDM signal. A 10 GHz repetition rate, 1.5 ps pulse train from an MLLD at 1550 nm was compressed using a 500-m long
Fig. 2.23 Experimental setup for C-to-L wavelength-band conversion of a 640 Gb/s OTDM signal.
dispersion decreasing fiber to the pulse width of 700 fs. It was split in two, with one part used for the 640 Gb/s C-band OTDM signal and the other for the control signal of the wavelength-band converted L-band 640 Gb/s OTDM signal DEMUX. A compressed pulse train was modulated with a 10 Gb/s PRBS of $2^{23} - 1$, and it was optically multiplexed to 640 Gb/s using a PLC. The pump wavelength $\lambda_p$ was set to 1565.0 nm, and the 1 MHz frequency modulated CW pump power $P_p$ was set to 24 dBm. After polarization optimization, the signal and pump were coupled into HNL-DSF #1 to generate FWM. A wavelength-band converted 640 Gb/s signal at 1580 nm was extracted by rejecting the pump wave using a fiber bragg grating filter and amplified using an L-band EDFA. It was optically DEMUX to 10 Gb/s in an NOLM composed of HNL-DSF #2 controlled by a 10 GHz, 700 fs C-band pulse train. BERs of the DEMUX 10 Gb/s L-band signal were measured using an optical preamplified receiver.

Figure 2.24(a) shows the optical spectrum measured at the output of HNL-DSF #1. A 640 Gb/s C-band OTDM signal was wavelength-band converted to L-band centered at 1580 nm. Figure 2.24(b) shows the streak camera traces of the wavelength-band converted 640 Gb/s signal and DEMUX 10 Gb/s signal. The pulse width of the DEMUX signal was measured to be 850 fs, and no adjacent pulses were observed. Thus, the 640 Gb/s OTDM signal was wavelength-band converted without significant pulse-width broadening. Figure 2.24(c) shows the measured BERs of DEMUX wavelength-band converted signals. These results indicate that C-to-L wavelength-band conversion of 640 Gb/s OTDM signal was successfully demonstrated at BERs less than $10^{-9}$.

2.5.4. **L-TO-C WAVELENGTH-BAND CONVERSION OF A 640 GB/S OTDM SIGNAL**

Figure 2.25 shows the experimental setup of L-to-C wavelength-band conversion of 640 Gb/s OTDM signal. For the generation of an L-band 1.5 ps pulse train, SC was generated [14] pumped by a 10 GHz, 1.5 ps, 1560 nm, MLLD pulse train followed by spectrum slicing at 1580 nm using a 3-nm filter. It was compressed using a 500-m long dispersion decreasing fiber to the pulse width of 780 fs. It was split in two, and one part was used for the 640 Gb/s L-band OTDM signal and the other for the control signal of wavelength-band converted C-band 640 Gb/s OTDM signal DEMUX. After 10 Gb/s data modulation and 640 Gb/s
optical multiplexing, it was combined with a CW pump and launched into HNL-DSF #1 to generate FWM. A wavelength-band converted 640 Gb/s signal at 1550 nm was extracted by rejecting the pump wave and amplified using a C-band EDFA. It was optically DEMUX to 10 Gb/s in an NOLM composed of HNL-DSF #2 controlled by a 10 GHz, 780 fs L-band pulse train. BERs of the DEMUX 10 Gb/s C-band signal were measured using an optical preamplified receiver.

Fig. 2.24  (a) Optical spectrum at the output of HNL-DSF #1. (b) The streak camera traces of the wavelength-band converted 640 Gb/s signal (upper trace) and DEMUX 10 Gb/s signal (lower trace). (c) The measured BERs of DEMUX C-to-L-wavelength-band converted signals.
Fig. 2.25   Experimental setup for L-to-C wavelength-band conversion of 640 Gb/s OTDM signal.
Figure 2.26(a) shows the optical spectrum measured at the output of HNL-DSF #1. A 640 Gb/s L-band OTDM signal was wavelength-converted to a C-band centered at 1550 nm. Figure 26(b) shows the streak camera traces of the wavelength-band converted 640 Gb/s signal and DEMUX 10 Gb/s signal. The pulse width of the DEMUX signal was measured to be 860 fs. No adjacent pulses were observed. Thus, the

![Optical spectrum](image1)

![Streak camera traces](image2)

![Bit error rate](image3)

**Fig. 2.26** (a) Optical spectrum at the output of HNL-DSF #1. (b) The streak camera traces of the wavelength-band converted 640 Gb/s signal (upper trace) and DEMUX 10 Gb/s signal (lower trace). (c) The measured BERs of DEMUX L-to-C-wavelength-band converted signals.
L-band 640 Gb/s OTDM signal was also wavelength-band converted without significant pulse-width broadening. Figure 26(c) shows the measured BERs of DEMUX wavelength converted signals. These results indicate that L-to-C wavelength-band conversion of a 640 Gb/s OTDM signal was successfully demonstrated at BERs less than $10^{-9}$.

2.5.5. SUMMARY OF SECTION 2.5

We have experimentally demonstrated 640 Gb/s OTDM signals interwavelength-band conversions between C- and L-bands accompanied by 640-to-10 Gb/s OTDM DEMUX. By use of HNL-DSFs, almost pulse broadening-free, highly efficient wavelength-band conversions were successfully demonstrated at BERs less than $10^{-9}$. This scheme could be a key technology in wavelength-band path routing in hierarchical hybrid OTDM/WDM networks.

2.6. Polarization-Mode Dispersion and Its Equalization

Polarization-mode dispersion (PMD) has become one of the remaining limitation factors for next-generation high-bitrate transmission systems. To the first order, PMD can be represented by a differential group delay (DGD) between the two principal states of polarization (PSP) [36]. Since the birefringence of a fiber varies randomly along a fiber link, DGD is a random variable that has a Maxwellian probability density function. The mean DGD grows as the square root of the length of the system. There have been an increasing number of reports on the harmful effects of PMD from the time-dependent, randomly varying birefringence in the installed fiber. There have also been several experiments to demonstrate first-order PMD compensation [37]. These were accomplished by delaying one state of polarization (SOP) with respect to the other by the amount of DGD.

This section describes the two types of polarization-mode dispersion equalizations:

- Using a lattice circuit
- Using the nonlinear effects of transmission fiber
2.6.1. POLARIZATION-MODE DISPERSION EQUALIZATION

We have demonstrated an optical lattice circuit to compensate for PMD, including higher orders, by realizing an inverse circuit of a transmission fiber [38]. This circuit is suitable for optical integrated circuits, but PMD monitoring is limited by the electric circuit frequency response. For the ultrahigh-speed OTDM scheme, all-optical PMD monitoring is needed to control the programmable optical circuit for PMD equalization.

We have proposed an optical lattice-circuit PMD equalizer controlled by the nonlinear optical product of two orthogonally polarized received signals [39]. Figure 2.27 shows a schematic diagram of this PMD equalizer. The PMD equalizing circuit is synthesized using only variable phase shifters in MZ lattice circuits. The output of the PMD equalizing circuit is amplified and fed to an optical multiplier employing a quasi–phase matching LiNbO$_3$ (QPM-LN) [39]. The nonlinear optical product of the two orthogonally polarized electric fields is detected by a photodiode and is used as the control signal for the PMD equalizing circuit. The maximum of

![Fig. 2.27](image)

**Fig. 2.27** Adaptive equalization of polarization mode dispersion employing optical nonlinear signal processing for controlling a variable MZ lattice circuit.
the QPM-LN output corresponds to the optimal condition for the PMD compensating circuit. Figure 2.28 shows optical pulses spread by the first-order PMD. The QPM-LN has a single-mode waveguide structure, which is capable of making the second harmonics of $E_x$ and $E_y$ of the QPM-LN c-axis. The time average of product $E_x E_y$ is proportional to the overlap integral of $E_x E_y$. As the product of $E_x E_y$ increases, the delay time difference and distortion of $E_x$ and $E_y$ decrease, so that PMD is compensated.

This is also true for higher-order PMD. We simulated the novel PMD equalizer operation for high-speed NRZ transmission at bitrate of 1 Tbit/s. A typical DSF of 100 km long is assumed as a transmission line. Figure 2.29 shows eye diagrams with and without equalization. The first-order PMD is 1.2 ps, and the second-order PMD is 0.4 ps$^2$.

The PMD equalizing circuit used in our experiment consists of two types of polarization-maintaining fibers (PMF) A and B, as shown in Figure 2.30. Type A is a 1-m long, 2.5 $\mu$m-outer diameter primary-coated PMF, which is used as a variable phase shifter employing a temperature-controller. Type B is an 80-m long, 0.9 mm outer-diameter nylon-coated PMF, which is used as a delay line considering smaller temperature dependence. Its temperature coefficient of delay time difference is smaller by two orders of magnitude than that of type A. The delay time is designed as the inverse of the bit rate. The splice angles between PMF units are illustrated in Figure 2.30. The total loss of the experimental lattice circuit was only 0.5 dB. The length of QPM-LN is 20 mm. The typical conversion efficiency is
Fig. 2.29  Eye diagrams of 1 Tbit/s OTDM signals with and without PMD equalization.

Fig. 2.30  A variable optical circuit for PMD equalization employing polarization-maintaining fibers.
about 100%/watt [40]. The QPM-LN output was more than 0.5 µW when the EDFA signal output was 12 mW, as shown in Figure 2.31. The signal wavelength was 1533 nm. The 3 dB-width of the QPM-LN was 0.35 nm. The PMD pulse distortion dependence of the QPM-LN SHG output was measured by using a PMF emulator, as also shown in Figure 2.31. Case A of 10 Gb/s pulse distortion yielded \(-65\) dB of SHG output, which corresponded to the first-PMD of 30 ps. Case B yielded \(-67\) dB of SHG output, which corresponded to the first-PMD of 160 ps.

### 2.6.2. **NONLINEAR POLARIZATION-MODE DISPERSION EQUALIZATION**

In nearly all of these experiments, the potentially significant effects of fiber nonlinearities on first-order PMD compensation were overlooked. The index of refraction can be changed by the optical power in a specific polarization state, resulting in a nonlinear birefringence [41]. The resulting performance penalty will vary significantly, depending on the details of the
dynamics of the SOP along the transmission line. We investigated experimentally how the nonlinear effects affect the SOP. Nonlinear suppression of PMD-induced pulse broadening by reducing the coupling of the polarization modes has been demonstrated experimentally in 10 Gb/s RZ signal transmission [42].

The transfer function matrix of the transmission line is expressed by Taylor expansion as [43]

$$T(\omega) = T(\omega_0) + \frac{dT}{d\omega}\bigg|_{\omega_0} \partial \omega + \frac{1}{2} \frac{d^2T}{d\omega^2}\bigg|_{\omega_0} \partial \omega^2 + L.$$  

(2.1)

When the transfer function matrix is expressed using phase parameters as

$$T(\omega) = \begin{pmatrix} \exp(-j\phi) & 0 & \cos \Theta & -\sin \Theta & \exp(-j\psi) & 0 \\ 0 & \exp(+j\phi) & \sin \Theta & \cos \Theta & 0 & \exp(+j\psi) \end{pmatrix} \exp(-j\Psi)$$

(2.2)

the basic parameters that characterize the polarization-mode dispersion are defined as the coefficients of the Taylor expansion as

$$\Theta(\omega) = \Theta(\omega_0) + \alpha_1 \partial \omega + \frac{1}{2} \alpha_2 \partial \omega^2 + L,$$

$$\phi(\omega) = \phi(\omega_0) + \beta_1 \partial \omega + \frac{1}{2} \beta_2 \partial \omega^2 + L,$$

$$\psi(\omega) = \psi(\omega_0) + \gamma_1 \partial \omega + \frac{1}{2} \gamma_2 \partial \omega^2 + L.$$  

(2.3)

For the first-order PMD shown in Figure 2.32, $\alpha_1$, $\beta_1$, $\gamma_1$ represent the polarization-mode coupling, the group delay, and the combination of polarization-mode coupling and group delay, respectively [43]. A 81.3-km dispersion compensated link was used as a test fiber. It consisted of 77.6 km of nonzero-dispersion shifted fiber (NZ-DSF) and 3.7 km of dispersion compensated fiber. The total zero-dispersion wavelength was 1550.5 nm, and the dispersion slope was 0.018 ps/nm/km/nm. In order to characterize the nonlinear effects on PMD parameters, we measured the transfer function of the fiber being tested using the Jones-Matrix-Eigen analysis method, in which the input power of the tunable CW laser is varied. Figure 2.33 shows the measured transfer function matrix element $|T_{11}|$ plotted versus the wavelength. By increasing the input power, the variation of transfer function could be reduced. Figure 2.34 shows the measured parameters when input powers were 0, 10, and 15 dBm. By increasing the nonlinearity, the variation and the absolute value of both the polarization-mode coupling
Eigen values of operator $D$:

$$\lambda_1, \lambda_2 = \pm \sqrt{\alpha_1^2 + \beta_1^2 + \gamma_1^2 + 2\beta_1\gamma_1 \cos 2\Theta_0}$$

1st order PMD: $T_{pmd} = 2\sqrt{\frac{\alpha_1^2}{\alpha_1^2 + \beta_1^2 + \gamma_1^2 + 2\beta_1\gamma_1 \cos 2\Theta_0}}$

**Fig. 2.32** Physical representation of basic polarization parameters.

**Fig. 2.33** Power dependence of transfer function matrix elements.
parameter $\alpha_1$ and the group delay parameter were reduced. Figure 2.35 shows the measured first-order PMD versus the wavelength. First-order PMD was greatly suppressed by utilizing the fiber nonlinearity, and the result agrees with those shown in Figure 2.34.

We measured the effect of nonlinearity on PMD compensation in 10 Gb/s RZ signal transmission, as shown in Figure 2.36. An MLLD pulse train with a 1.5 ps pulse width and 2.1 nm spectrum width was used as the signal source. To avoid wavelength dispersion effects, the signal wavelength was set to the zero wavelength of the test fiber. Input power was varied by changing the EDFA gain, and input SOP was varied by a polarization controller of the transmission side. BER was measured by using an optical preamplified receiver.

Figure 2.37 shows the measured BERs when the input SOPs were linear polarization and right-hand circular polarization of various input powers. For all of the input SOPs, BER improved with increasing input power. Pulse-width variations of the output pulse, with respect to the input pulse,
Fig. 2.35  Power dependence of first-order PMD.

Fig. 2.36  Experimental setup for measuring the nonlinear effects in 10 Gb/s RZ signal transmission.
were 19.3% and 9.2% when the peak powers of the input pulse ($P_{pk}$) were 22 dBm and 37 dBm, respectively. These results were obtained because by increasing the nonlinearity, both the coupling parameter and the group delay parameter were reduced and first-order PMD was suppressed.

2.6.3. SUMMARY OF SECTION 2.6

We proposed a novel PMD equalizer using the optical nonlinear product of orthogonally polarized electric fields as control signals. The QPM-LN SHG output dependence on PMD degradation and the PMD behaviors of an equalizing lattice circuit were confirmed. Also, we have investigated experimentally the characteristics of the nonlinear effects on the basic parameters of PMD. The nonlinear suppression of PMD-induced pulse broadening by reducing the coupling of the polarization modes has been experimentally demonstrated in 10 Gb/s RZ signal transmissions. This passive PMD
suppression scheme without active control is an alternative solution in PMD compensation.

2.7. Conclusion

Hybrid hierarchical OTDM/WDM networks are discussed by reviewing all-optical signal processing technology in our experiments. Ultrahigh-speed OTDM beyond electronic device operation speed requires all-optical signal processing for economical realization. Supercontinuum technology is applicable to realizing WDM carrier generation, WDM and OTDM format conversion, and wavelength-band conversion. The nonlinear optical devices demonstrated are nonlinear optical fibers and SMZ semiconductor gates. Future studies are expected to realize more functional hybrid hierarchical OTDM/WDM networks.

References


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Part 2 | Critical Technologies
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3.1. Path Technologies

3.1.1. ROLE OF PATH

For more than 100 years, we have been developing public telecommunications networks and the necessary technologies. To develop robust and very large-scale networks, effective traffic engineering capabilities are necessary, and techniques have been developed for each transfer mode network, such as PDH (plesiochronous digital hierarchy), SDH (synchronous digital hierarchy), and ATM (asynchronous transfer mode) networks. Until 10 years ago, the major service being considered was the plain old telephone.

Among the traffic engineering techniques developed for transport networks, the concept of the path is of critical importance. First, the SDH and ATM path mechanisms will be briefly reviewed, and it will be explained how they are utilized in existing networks. Path technology is evolving together with transfer technology. Matching the advances made in optical technologies, the optical path concept was proposed in 1992, and the necessary technologies have been under continuous development since that time [1]. The characteristics of optical paths are explained in this chapter.

The transport network layered architecture of the public telephone-based network is illustrated in Figure 3.1. A telecommunication network can be divided into two network layers: a service network layer and a transport
Fig. 3.1 Layered architecture of public telecommunication network. Source: Ken-ichi Sato, Advances in Transport Network Technologies, Artech House, Norwood, MA, 1996.
network layer. The service network layer consists of circuits and flows. Service networks provide public switched telephone service, leased-line service, Internet service, and so on. The transport network layer consists of path networks and physical media networks. The physical media networks include optical fiber and radio wave transmission systems. The path networks bridge the physical media network and circuit networks. The service networks are logical networks and are service dependent; the transport network layer (the physical media networks and path networks) is, on the other hand, less service dependent and is the platform on which telecommunications networks are realized.

Figure 3.2 schematically explains the role of paths. A path is a group of circuits or flows or, more generally, a unit of network operation, design, and provisioning. Basic path attributes are route, bandwidth, and/or QoS (quality of service). Furthermore, effective service protection can be performed by controlling paths upon network failure. Recently, high-speed optical fiber transmission systems have been introduced widely; as a result, the severity of single transmission link failure has been enhanced. For example, a 2.5 Gb transmission system accommodates 32,000 64 kbit/s circuits, and a single fiber failure cuts all the 32,000 circuits. In the event of a transmission link failure, circuit-by-circuit protection or restoration is very difficult; the importance of path-layer protection or restoration is obviously significant. Thus, the paths provide an effective way of realizing traffic engineering. Path control can be performed with ADM (add/drop multiplexer) systems and/or digital cross-connect systems and network operation systems.
Network flexibility is enhanced with path layer control. Paths also provide an effective means of implementing virtual private networks (VPNs).

In Section 3.1.2, the path technologies realized in different transfer mode networks are explained.

### 3.1.2. ELECTRICAL PATH TECHNOLOGIES

#### 3.1.2.1. Digital Path in SDH Networks

The worldwide unique network node interface (NNI) based on SDH was first standardized in 1998 in ITU-T (international telecommunication union telecommunication standardization sector, formerly CCITT). SDH systems were deployed worldwide in the 1990s, replacing PDH systems. PDH networks employ different digital multiplexing hierarchies in Europe, North America, and Japan. Thus, seamless connections of digital paths are not possible. Furthermore, the asynchronous nature of digital paths required bit-stuffing during multiplexing, so it was not possible to access lower-order paths in the line signal structure directly; step-by-step demultiplexing of multiple path hierarchies was needed. The introduction of SDH provided a simpler alternative to PDH path networks; the direct multiplexing/demultiplexing of paths allows the digital cross-connect/ADM function and transmission signal monitoring capabilities to be implemented easily [2, 3].

Figure 3.3 illustrates an SDH-based transport network. Two stage paths are utilized: VC-1n (virtual container 1n; the payload capacity is 1.544 Mb/s for VC-11, used in North America and Japan, and 2.048 Mb/s for VC-12, used in Europe) and VC-4 (the payload capacity is 139.264 Mb/s). VC-1n is called the lower-order path, and VC-3 (payload capacity is 44.736 Mb/s) and VC-4 are called the higher-order paths. As mentioned before, the path serves as the basic unit of network operation, design, and provisioning. For service access, the appropriate path bandwidth is determined by the service bandwidth and the traffic demands. For telephone networks, the path bandwidth for service access was that of 24 or 32 64 kb/s channels (VC-11 or VC-12). The transmission link speed, however, is independent of this service access path speed, and the available bandwidth is increasing rapidly due to recent advances in optical transmission technology. TDM speeds of 10 Gb/s are now commercially available.

In order to exploit fully the large capacity transmission of optical fiber, it is necessary to realize cost-effective access to the transmission system.
This function is called *transmission access* (or *transaccess* for short), and the higher-order paths provide this function. A higher-order path may accommodate different lower-order service path networks, such as a telephone service and leased line service network, and also provide transport capability between higher-order path terminating nodes. Hence the path network can be hierarchical, and effective grooming capability is required at path cross-connect nodes. This is realized by the ADM and/or cross-connect systems. The lower-order path network is accommodated within the higher-order path network, and it is accommodated within the physical (fiber) network (see Figure 3.3). Service protection will usually be performed at the higher-order path level by switching the failed paths to protection/restoration paths.

### 3.1.2.2. Virtual Path in ATM Networks

In the 1980s, ATM technologies were extensively developed to create multimedia networks [2]. The early development stages considered only the virtual channel capability. The necessity of traffic engineering was identified, and the virtual path concept was proposed in 1987 [4].

The path is fundamentally a logical concept whose attributes are the bandwidth, route, and QoS that it provides, as stated before. In SDH networks, a path is tightly linked to the physical interface structure
for transmission. This linkage produces inefficiencies, which can become a serious handicap, given the popularity of multimedia services. For ATM networks, the virtual path was standardized in ITU-T in 1990 [5]. Virtual paths are identified by the label (VPI: virtual path identifier) carried in each cell header, as shown in Figure 3.4. This mechanism enables the separation of logical path aspects from the physical transmission interface structure, so the fully logical realization of path functions becomes possible. The route and capacity of paths can be defined independently, which provides the network with significant flexibility, among many other benefits [2]. The VP benefits compared to the digital paths in SDH/PDH networks are as follows:

- Simplification of interface and cross-connect node structure
- Simplification of path layer architecture (any bandwidth is possible)
- Simplification of path accommodation design (without multiple path hierarchies)
- Network cost reduction
- Enhanced network flexibility

The virtual paths are cross-connected using the ATM cross-connect function, which performs cell switching according to the VPI.

Fig. 3.4 ATM Virtual Path.
3.1.2.3. Label Switched Path in IP Networks

Internet traffic has been continuously exploding since the early 1990s, when the commercial World Wide Web emerged and modern browsers were released. Data traffic, including Internet traffic, exceeded that of voice in 1996 in North America and is expected to achieve the same dominance throughout the rest of the world soon. IP router technologies have progressed continuously to match the IP traffic increase. Routers based on software routing have been replaced by hardware routing realized with ASICs (application-specific integrated circuits), which have greatly enhanced router throughput.

In the early stages of Internet development, the IP network was only one part of the telecommunications network, and IP routers were connected to each other using SDH digital paths (leased line), as depicted in Figure 3.5. IP packets were transported and routed node by node, because there was no native path capability in IP networks. Soon, the IP network was recognized as a network that could deliver almost all services, including real-time services, such as telephone and real-time video transmission. The IP protocol was, however, designed originally for data transmission and so lacked strict QoS (delay and reliability) guarantees. The IP network lacked the mechanisms needed for the traffic engineering that would realize high-quality, robust, and large-scale networks.

![Fig. 3.5 SDH-based IP backbone network configuration.](image-url)
To cope with these problems, ATM technologies have been introduced as the underlying transfer mechanism to provide the path functions. Routers can be interconnected directly with VPs or VCs. This technology was called IP over ATM (see Figure 3.6). The technology enabled node cut-through (see Section 3.2.2.), and thus increased network throughput. The VPs/VCs also provide a basis for network traffic engineering. Most large-scale IP backbone networks installed in the late 1990s are based on this technology.

In this approach, the ATM and IP layers are managed separately. It follows that the number of VPs/VCs needed to connect all \( n \) IP routers is of the order of \( n^2 \), which increases the IGP (interior gateway protocol) processing load and limits the scale of the network. An IP packet is divided into many cells at the ingress node of the ATM backbone network, and the cells are reordered and reassembled into the original packet at the egress node. The SAR (segmentation and reassembly) processing burden limited the interface speed of IP over ATM to around 2.5 Gb/s in the early 2000s.

In order to overcome these difficulties, a more IP-oriented technology, MPLS (multiprotocol label switching) [6], was developed in the late 1990s. MPLS integrates IP and data-link layer technologies. The MPLS network configuration is illustrated in Figure 3.7. With MPLS, LSPs (label switched paths) are defined, which are realized by applying shim labels to each
packet. The shim header has link local significance, as does the VPI in ATM cells, and the value is swapped link by link (label swapping). The LSP concept includes ATM VP realization, and various other layer-2 technologies can be utilized to implement LSPs.

The major difference between this technology and IP over ATM in terms of management is the integrated management capability of layer-3 and shim-layer (layer-2.5) networks. MPLS provides a powerful mechanism with which to realize robust and global-scale IP backbone networks and VPNs, by realizing path layer functions under the IP layer (layer 3). Thus, the path functions must be seen as a crucial mechanism if the IP network is to become the infrastructure of high-quality multimedia service delivery.

3.2. Optical Path Technologies

3.2.1. OPTICAL PATH

The point-to-point transmission capability has been increased by more than two orders of magnitude in the last decade through the introduction of optical fiber transmission, and 10 Gb per channel transmission
systems are now being introduced. In this context, it is necessary to realize cost-effective transaccess and effective grooming capability at the nodes. Existing SDH and ATM cross-connect systems and IP routers can evolve with the enhancements of existing electrical device technologies. One limit is, however, emerging in cross-connect node throughput; it stems from the semiconductor process technology limit. The optical path concept was proposed to break through this limit [2, 7]. Optical paths are identified by their wavelengths. Optical paths can make quantum leaps in both transmission capacity and cross-connect throughput simultaneously by exploiting WDM (wavelength-division multiplexing) transmission and the wavelength routing capabilities of paths.

Various path realization technologies are compared in Table 3.1 in terms of path identification and routing mechanisms. The paths realized in layer 2 are identified by the label/header attached to each packet/cell. The digital paths for SDH and PDH in layer 1 are identified by time position in the TDM

<table>
<thead>
<tr>
<th>Multiplexing Technologies</th>
<th>Path Technologies</th>
<th>Path</th>
<th>Identification (# of Paths/Link)</th>
<th>Soft/Hard Routing</th>
<th>Routing</th>
</tr>
</thead>
<tbody>
<tr>
<td>PDH</td>
<td>Digital path</td>
<td>Time position in the TDM frame (&lt;192)</td>
<td>Hard</td>
<td>Time slot interchange + Space switch Store-&amp;-forward electrical processing + space switch Store-&amp;-forward electrical processing + space switch Waveguide router (self-routing) and/or space switch</td>
<td></td>
</tr>
<tr>
<td>SDH</td>
<td>(VC-1n, VC-3/4)</td>
<td>Cell header (VPI) (&lt;4096; NNI &lt;128; UNI)</td>
<td>Soft</td>
<td></td>
<td></td>
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<tr>
<td>ATM</td>
<td>VP</td>
<td>Shim label (&lt;2^16)</td>
<td>Soft</td>
<td></td>
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<tr>
<td>Packet</td>
<td>LSP</td>
<td>Wavelength (&lt;1,000)</td>
<td>Hard</td>
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<tr>
<td>WDM</td>
<td>Optical path</td>
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frame. In WDM, on the other hand, wavelengths are utilized to identify paths. The characteristics of wavelength routing are

- Hardware routing enables large routing node throughput.
- Store and forward-based routing is very difficult, due to a lack of efficient optical memory.
- Routing in a new dimension (wavelength) allows different format signals to be routed through the same optical fiber at the same time.

By exploiting the advantages of WDM and wavelength routing, we can realize photonic transport systems that offer relatively small size, low power consumption, and extremely large routing throughput. Available path granularity and number of paths per fiber are, however, limited. Path capacity will be more than several hundred megabits per second, and the number of available paths per link is usually less than 1000. Hence, today, the most attractive application of optical paths should be to create large bandwidth transaccess paths between nodes or node systems, as illustrated in Figure 3.8. Electrical paths, such as digital paths, VPs, and LSPs, will be utilized as service access paths to provide specific services and to realize the traffic engineering needed. If the cost effectiveness of WDM, compared to TDM, can be attained at smaller path bandwidths in the future, the applicability of optical paths will be enhanced. Optical paths are not

**Fig. 3.8** Application of optical paths.
seen as replacing all electrical paths at present, but as complementing them, in the form of transaccess paths, for example. Optical path networks will accordingly be introduced by overlaying existing electrical path-based networks.

3.2.2. CHARACTERISTICS AND BENEFITS OF OPTICAL PATH NETWORKS

Characteristics of optical paths are summarized as follows:

- Exploiting WDM transmission enhances transmission capacity.
- Wavelength routing enhances cross-connect node throughput.
- Flexible and progressive transport capability is effectively furnished.
- Transport platform provided.
- Effective network protection/restoration can be done.
- Available path granularity and number of paths per fiber are limited (path capacity > Gb/s, number of paths per fiber < 1000).

Some of these points are explained further in the sections that follow.

3.2.2.1. Cross-Connect Node Throughput Enhancement

Transmission capacity multiplication will be achieved with WDM. The cross-connect node throughput can be expanded by utilizing wavelength routing. The throughput of an optical path cross-connect system can be much larger than that of an electrical TDM cross-connect system, and the hardware can be simple even when the traffic volume is very large. This is because wavelength routing that is insensitive to the path capacity requires only passive optical devices; no synchronization is needed among the optical paths (the WDM channels do not need to be synchronized).

Figure 3.9 shows the advances made in NTT's networks with regard to cross-connect node throughput. Cross-connect systems were first put into commercial use by NTT in 1980 for the PDH network. They employ DS2 (6.3 Mb/s) interfaces with line facilities, and the unit of cross-connection with time slot interchange techniques is 384 kb/s, or six telephone channels. The throughput of the cross-connect system has been increasing in line with the introduction of SDH in 1989 and ATM in 1994. The throughput increase factor is about 60 times per decade. The throughput increase offered by the latest IP routers is significant, as shown in Figure 3.9. They now reach the existing cross-connect node throughput, but such routers have difficulty in offering the completely nonblocking characteristic available in
existing transport systems. Optical cross-connect nodes that utilize WDM and wavelength routing can offer much larger throughput, as shown in Figure 3.9, although the path granularity may not be as fine as that of electrical systems (for OXCs shown in Figure 3.9, the optical path bandwidth is 2.5 Gb/s or more).

### 3.2.2.2. Network Throughput Enhancement with Optical Cut-Through

Figure 3.10 compares existing IP over WDM with optical path technologies (i.e., photonic MPLS, which is discussed in Section 3.2.4). In the existing IP over WDM network, in order to access the optical fiber transmission link, all WDM signals in the line must be converted into electrical signals and terminated at each node. The entire signal capacity on each link must be electrically routed (packet by packet), based on each packet header, and this processing is done node by node. In IP networks, most packets simply go through the node, and only a small portion of total link capacity must be terminated at each node. If the transit traffic is routed without conversion to electrical signals and without packet-by-packet processing, IP processing at the node is minimized and the total node throughput will be greatly increased. This can be realized by utilizing optical paths and wavelength...
Routing; optical path routing is possible with passive optical components, as is explained in section 3.3.2. This technique will eliminate the traffic jams seen in existing routing nodes. This is a remarkable advantage when the total link capacity is very large, because it minimizes serial-to-parallel conversion of the high-speed bit stream and subsequent necessary electrical processing. The electrical processing bottleneck can thus be eliminated or mitigated by introducing optical paths.

Applying optical paths provides another level of routing that is not packet-by-packet routing. Figure 3.11 shows the degree of node throughput enhancement possible with a PTS (photonic transport system) that has an optical path ADM or cross-connect function. The cluster efficiency of IP routers is parameterized. The cluster efficiency is defined as the total throughput of the router cluster divided by [the number of component routers multiplied by the component router throughput]. If the efficiency is 50% and the ratio of pass-through traffic at a node is 0.75, the application of PTS enhances the total node throughput by a factor of eight when the same throughput IP router is used. Generally speaking, cluster efficiency decreases as the number of component IP routers increases, and the
effectiveness of PTS will become more and more significant in designing large throughput networks.

3.2.2.3. End-to-End Node Cost Reduction

Network cost can be reduced by applying optical paths (IP over photonic) to a large throughput network. Figure 3.12 exhibits an example of an end-to-end cost evaluation [7] using the model depicted in the figure. For the cost evaluation, 2.5 Gb/s IP router interfaces and 20 Gb/s transmission per fiber (eight wavelength multiplexing) were assumed. Only node cost was assessed, because the transmission cost is an insignificant part of overall network cost due to the benefit of WDM transmission. Two node-cost-ratio patterns were evaluated, as shown in Figure 3.12. In both cases,
it is obvious that applying the PTS cross-connect reduces the total node cost compared to the all-electrical IP router approach (IP over WDM). As the number of intermediate nodes increases, this cost advantage becomes more significant, as shown in the figure. This is because the routing of large-capacity optical paths reduces the intermediate node cost.

### 3.2.2.4. Graceful Expansion of Optical Cross-Connect System Throughput

Optical paths are asynchronous to each other, so it is very easy to multiplex and demultiplex high-speed paths, because bit synchronization is not needed. This nonsynchronous characteristic enables us to devise a cross-connect system with high modular growth capability, which can be achieved with TDM [8]. This yields a cross-connect node that enables incremental throughput growth in terms of the number of wavelengths per fiber, optical fiber count, and channel bitrate to meet any increase in demand. This is depicted in Figure 3.13. This is an important point for the economical introduction of optical cross-connect systems, because the required throughput at the outset is not so large. Given the vast throughput possible, the high modular growth capability offers the economical introduction of optical cross-connect systems to transport nodes whose needed throughput range from small to large [2].
3.2.2.5. Provision of Transport Platform

For IP services, different technologies—such as IP over ATM over SDH/SONET over WDM or IP over SDH/SONET over WDM—have been developed. Figure 3.14 shows an example of the functional duplication in terms of IP packet transportation. Multiple layer entities are utilized, as shown in Figure 3.14, and some of the functions in each layer are duplicated. Each layer has multiplexing functions, and some have routing functions and protection and/or restoration functions. Not only duplication, but also collision may occur among the different layers in terms of network protection/restoration against failure.

Simplification of the network layer relation and minimization of functional duplication are important in realizing effective networks. This can be done effectively by exploiting photonic network technologies. In WDM-based photonic networks, the optical path can be designed to accommodate different electrical signal formats, as mentioned before; different electrical transmission formats can be carried via a single optical fiber through wavelength assignment. This is possible due to the asynchronous nature of each optical path (wavelength) and the lower layer multiplexing capability of WDM. It is obvious that the optical path can provide a platform that can carry many different transfer modes.

In addition, with existing TDM technologies, signal mapping relations tend to be complicated, and a lot of standardization effort is required to specify them, which often delays service provision. The direct accommodation
of various format signals minimizes this problem. The introduction of the optical path platform allows new services to be introduced with minimal delay and reduces the difficulty of upgrading network functionality.

Figure 3.15 compares existing electrical routing networks with a photonic transport network that is based on optical path technologies. There are two keys to the new photonic transport network shown in Figure 3.15. One is the simplification of the core transport network, where routing requires only wavelength routing and thus only one kind of routing entity, OXC (optical cross-connect)/OADM (optical add/drop multiplexer) is used; different format electrical signals are effectively accommodated within the optical layer. The other is separation of core and edge functions; the core network provides abundant transport capability with large-throughput optical nodes and large-capacity WDM transmission links. The electrical processing nodes, which lie in the edge network, will be connected using direct optical paths. The core network will also ensure high integrity with optical path protection/restoration capability. Of course, the core network
Fig. 3.15  Existing network and photonic transport network—simple core network utilizing wavelength routing.
will not be constructed overnight but will be implemented by overlaying existing networks, and it can grow as new services are introduced.

3.2.3. **WAVELENGTH PATH AND VIRTUAL WAVELENGTH PATH**

Optical paths are identified by their wavelengths and can accommodate electrical paths. There are two types of optical paths: WPs (wavelength paths) and VWPs (virtual wavelength paths) [1, 2].

In the wavelength path scheme, an optical path is established between two nodes by allocating one wavelength to the path (see Figure 3.16a). The intermediate nodes along the WP perform WP routing according to the wavelength.

In the VWP scheme, VWP wavelength is allocated link by link, and thus the wavelength of each VWP on a link has local significance instead of global significance, as is true for WPs (see Figure 3.16b). This is similar to the VPI (virtual path identifier) assignment principle in ATM networks. For this reason, this scheme is called *virtual WP*. In the VWP scheme, wavelength conversion is necessary at cross-connect nodes. Path termination is not needed.

The VWP scheme has various advantages over the WP scheme [1]. They include

- Simple path accommodation design
- Higher flexibility in network expansion
- Fewer network resources (wavelengths or fibers) required

The single and major disadvantage of the VWP scheme is that it entails wavelength conversion at cross-connects. This will be the key in determining the effectiveness of the VWP scheme.

3.2.3.1. **Optical Path Accommodation**

As shown in Figure 3.16, to establish four WPs and four VWPs with the same routes, the WP scheme requires three wavelengths, whereas the VWP scheme requires only two. The VWP scheme, therefore, maximizes the degree of wavelength reuse in the network so that fewer wavelengths are needed.
Note: only one transmission line between nodes is shown for bi-directional ones.

(a) Wavelength Path

<table>
<thead>
<tr>
<th>In</th>
<th>Wavelength (WP)</th>
<th>Out</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>(\lambda_1) (WP 1)</td>
<td>2</td>
</tr>
<tr>
<td>2</td>
<td>(\lambda_2) (WP 2)</td>
<td>4</td>
</tr>
<tr>
<td>4</td>
<td>(\lambda_2) (WP 2)</td>
<td>1</td>
</tr>
<tr>
<td>4</td>
<td>(\lambda_3) (WP 3)</td>
<td>2</td>
</tr>
</tbody>
</table>

(b) Virtual Wavelength Path

<table>
<thead>
<tr>
<th>In</th>
<th>Wavelength (VWP)</th>
<th>Out</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>(\lambda_1) (VWP 1)</td>
<td>2</td>
</tr>
<tr>
<td>2</td>
<td>(\lambda_2) (VWP 2)</td>
<td>4</td>
</tr>
<tr>
<td>2</td>
<td>(\lambda_1) (VWP 1)</td>
<td>1</td>
</tr>
<tr>
<td>4</td>
<td>(\lambda_2) (VWP 3)</td>
<td>4</td>
</tr>
<tr>
<td>4</td>
<td>(\lambda_1) (VWP 2)</td>
<td>1</td>
</tr>
<tr>
<td>4</td>
<td>(\lambda_2) (VWP 3)</td>
<td>2</td>
</tr>
</tbody>
</table>

(c) WP routing table example in node A

(d) VWP routing table example in node A

* : same number is used for incoming and outgoing lines for simplicity

Fig. 3.16  Comparison of WP and VWP. Reprinted with permission from *Advances in Transport Network Technologies*, by Ken-ichi Sato, Artech House, Inc., Norwood, MA, USA, 1996.
In the WP accommodation process, the wavelength assignment problem must be solved simultaneously with the routing problem, so that a different wavelength is assigned to each WP among WPs in the same physical link throughout the network. In determining the optical path route and the wavelength, optimization is necessary for the required network resources (number of fibers or wavelengths in a network). The problem is known to be NP-complete [9], where the exact solution is not obtained in polynomial time. To cope with this, heuristic path accommodation design algorithms that are applicable to large-scale optical path network design have been developed [10, 11].

In optical path accommodation, the objective functions differ with the target network. For example, in the bus or chain network architecture that may be used in local area applications, each station or node is connected with a single fiber (or bidirectional fibers). In such LAN applications, the objective function might be the minimization of blocking probabilities to establish optical paths under the constraint of a fixed number of available wavelengths.

Figure 3.17 compares resource (fiber count) requirements of the WP and VWP schemes to accommodate a certain number of optical paths. WP/VWP accommodation design algorithms that take link failure restoration into consideration and that minimize the required number of fibers in the network were used [12]. The algorithms guarantee 100% restoration against any one link failure in the network. The physical topology used in the simulations is the 24-node (4 by 6) regular structure network shown in Figure 3.17. Ten different random traffic patterns for each path demand (horizontal axis) were assumed; each result is the average of the ten trials. Upstream and downstream paths are set to follow the same route. The number of wavelengths, $M$, that can be multiplexed in a fiber is set to be 8 and 32. The evaluated fiber counts include the intraoffice fiber ports (connected to electrical systems within the node) needed for terminating traffic at the node. It is shown that the WP scheme requires about 20% more fibers than the VWP scheme when $M$ is 8, and about 40% more when $M$ is 32.

Figure 3.18 illustrates another example of an IP-backbone network model. In this model, 25 or 50 IP nodes are connected in a mesh configuration, where 1 plus 1 diverse routing is applied for protection against network failure. Sixteen wavelengths are assumed to be multiplexed within one fiber, and the required number of PTS ports was evaluated for the physical network models shown in Figure 3.18. The WP scheme (no wavelength conversion at nodes) is assumed. With the model consisting of 25 nodes,
the required PTS port number is 17 for 80% coverage, and 32 ports, which can be realized with existing technologies, is the maximum requirement.

### 3. Optical Path Cross-Connect

**3.2.4. IP OVER OPTICAL PATH AND PHOTONIC MPLS**

Generic optical path technologies have thus far been discussed, but a more IP-oriented approach, photonic MPLS, is explained next. Two types of photonic MPLS are possible: one uses wavelengths as a label for a layer-1 bit stream, and the other uses wavelengths to label each block or packet. The latter approach, however, requires optical memory or a fast resource-management mechanism to prevent collisions of blocks/packets at nodes. Effective optical memories do not exist today and will be very difficult even in the future; a breakthrough in physics is required. In this section,
Input Data
- WP or VWP
- physical network topology
- path demands among nodes
- restoration scheme (same/different restoration path wavelength)

Network Design Algorithm
- minimize network resources
- plural links between nodes
- applicable to large scale network
- network restoration is considered

(a) Optical Path Accommodation Design Tool

Number of Nodes = 25
- WP (no wavelength conversion)
- path demand = full mesh
- number of WDM wavelength per fiber = 16
- protection: 1+1 diverse routing

Number of Nodes = 50

(b) Required OXC Port Number (including intra-office link)

Fig. 3.18 Optical path network design example.
the photonic MPLS that uses wavelengths as a label for a layer-1 stream is discussed.

Figure 3.19 compares MPLS to photonic MPLS. In MPLS, a layer-2 label is attached to each packet at an ingress router, and the label is swapped link by link. In photonic MPLS, a wavelength label is attached to a bit stream and each IP packet is accommodated within the wavelength path at the ingress router. With the WP mechanism, one wavelength is allocated to a path from ingress to egress router. With the VWP mechanism, the wavelength is swapped link by link.

Figure 3.20 depicts the IP over optical path network. In this network, optical paths will be established between IP nodes when there is enough traffic to fill optical path capacity. Full-mesh router connection will be realized in a higher layer (e.g., using MPLS). An IP router does not recognize optical layer routing functions (separated operation). The required IP router throughput can be much smaller due to optical cut-through, compared to when optical paths are not utilized (i.e., direct router connections with optical fibers). On the other hand, as shown in Figure 3.21, photonic MPLS utilizes wavelengths as a label. An optical labeled path accommodates IP packets that share the same route. Photonic MPLS routers switch (cross-connect) optical paths. The photonic MPLS layer can be a sublayer of packet-based electrical MPLS. IP (MPLS) routers recognize...
photonic MPLS routers. Integrated operation between IP and optical layers is performed through the IP signaling and label distribution protocol.

Table 3.2 compares MPLS to photonic MPLS. One of the major differences between MPLS and photonic MPLS is that MPLS allows label merge, whereas photonic MPLS does not. Another difference is that with photonic MPLS, the number of available LSPs per link is limited to less than
Table 3.2  Comparison of electrical MPLS and photonic MPLS.

<table>
<thead>
<tr>
<th></th>
<th>Electrical MPLS</th>
<th>Photonic MPLS</th>
</tr>
</thead>
<tbody>
<tr>
<td>Path</td>
<td>Label switched path (Label is attached to each packet)</td>
<td>Optical path (Label is attached to data stream)</td>
</tr>
<tr>
<td>Path state</td>
<td>Soft</td>
<td>Hard</td>
</tr>
<tr>
<td># of Paths/link</td>
<td>Can be very large ($2^{16}$)</td>
<td>Limited (&lt; 1,000)</td>
</tr>
<tr>
<td>Path bandwidth</td>
<td>Any</td>
<td>Usually fixed and large (Gb/s)</td>
</tr>
<tr>
<td>Label merge</td>
<td>Yes</td>
<td>Difficult</td>
</tr>
<tr>
<td>Label stack</td>
<td>Yes</td>
<td>Difficult</td>
</tr>
</tbody>
</table>

With the present level of technology, it follows that photonic MPLS technology will be first applied to the backbone network, where fine path granularity is not required. In MPLS, LSP can be hierarchical with the label stacking technique. This mechanism can be extended to realize the hierarchical photonic MPLS plane and electrical MPLS plane arrangement, as shown in Figure 3.22. The photonic MPLS plane will provide fat label switched paths that connect each MPLS domain in a meshlike configuration. MPLS routers (label switched routers [LSRs]) recognize photonic routers as LSRs. Photonic routers can be regarded as large-capacity MPLS routers. Optical label switched paths (OLSPs) are automatically reconfigured in accordance with changes in the requirements placed on the photonic MPLS plane.

The photonic router generic functional view is depicted in Figure 3.23. The photonic router consists of an electrical MPLS router part, an optical path cross-connect function, and a photonic transport payload assembler/disassembler (PAD), which performs UNI to/from NNI signal format conversion. The photonic MPLS controller controls those functions through the hardware manager.

3.3. Optical Path Cross-Connect System

The WDM optical path network offers functions that provide transport, multiplexing, routing, supervision, and survivability of client signals and that are processed predominantly in the optical domain. The optical path
Fig. 3.22 Photonic MPLS and MPLS hierarchical architecture.

Fig. 3.23 Photonic router logical configuration.

NNI: network node interface
UNI: user network interface
PTS: photonic transport system (OXC, OADM, etc.)
PAD: photonic transport payload assembler/disassembler (UNI from/to NNI converter)
cross-connect (OPXC) system will be the key to realizing the WDM optical path network because it acts as the transport node. This section focuses on the technologies essential to the design and the realization of the OPXC system.

3.3.1. **SYSTEM ARCHITECTURE**

3.3.1.1. **Generic Architecture and Requirements**

The typical OPXC system consists of optical cross-connect (OXC), wavelength conversion (W/C), WDM transmission (WDM-T), and payload assembler/disassembler (PAD) functions. The function block is shown in Figure 3.24. The W/C function is needed in the VWP network but not in the WP network. Needless to say, the latter is simpler than the former; however, the former offers lower complexity and simplifies wavelength assignment.

**Fig. 3.24** Functions required in optical path cross-connect node system.

OXC: optical cross-connect  
OADM: optical add/drop multiplexing  
WDM-T: WDM transmission function  
PAD: payload assembler/dis-assembler  
W/C: wavelength conversion
and network operation. Optical network-node interface (ONNI) is logically provided in the WDM-T on the transmission line side, and the optical user-to-network interface (OUNI) is established in the PAD on the legacy system side.

The OPXC system is designed to have $N$ input–output fiber ports, and is constructed to transfer a maximum of $M$ wavelength multiplexed signals in one fiber. In $N$ input–output fiber ports, $u$ ports are used for intraoffice interfaces via the PAD with electrical facilities, such as an electrical path cross-connect/switch system. Although the maximum number of wavelength-multiplexed signals, $M$, is different in each fiber-port in general, here it is assumed, without loss of generality, to be identical in order to simplify the discussion regarding the system architecture. The OPXC system can be imagined as an interchange for vehicles on a highway, where the connections are off-ramps and on-ramps over time, and the optical path, which carries electrical paths, is similar to a lane on a highway.

The OXC switches any input optical path to any output fiber port. The OXC function also includes the optical add/drop multiplexing (OADM) function that adds/drops optical paths to/from the PAD and multiplexes them, if necessary. Most WDM ring network systems implement only OADM functions. The OXC function must support cross-connection to each of the $N$ output fiber ports for each individual optical path, $N \times M$, in a strictly nonblocking manner, where a switch is strictly nonblocking if any input can always be connected in a viable way to any unused output without disturbing the existing connections. Blocking does not include the blocking caused by wavelength collision between input and output ports, which is difficult to prevent in the WP scheme.

The WDM-T function ensures high-quality WDM transmission performance between neighboring OPXC systems. Although bitrate transparency is ideal, the opto-electronic 3R function and performance-monitoring function (in other words, a transmitter) could be included in the WDM-T if needed, where the 3R function incorporates three fundamental functions for signal regeneration: reshaping, retiming, and regeneration. The transmitter retiming circuit limits the bitrate transparency, so an OPXC system that uses transmitters is called an opaque cross-connect system. When the distance between neighboring OPXC systems is beyond the limitation provided by the linear repeating performance, regenerative repeaters are inserted into the transmission line. On the other hand, the OPXC without any transmitter for through optical paths is called a transparent OPXC system.
Transparent OPXC systems and linear repeaters can create a bitrate transparent optical path network.

The PAD function accommodates client signals and terminates optical paths. Some OPXC systems do not need to implement this function block if intraoffice connection is not required in a node.

The W/C function literally works by changing input wavelength $\lambda_i$ into $\lambda_j$ as the output wavelength, where $i$ and $j$ represent integers from 1 to $M$. A generic W/C scheme is shown in Figure 3.25. Generally speaking, the OPXC system requires that either wavelength $\lambda_i$ or $\lambda_j$ be freely selectable. When $\lambda_i$ is changed by some selection mechanism, we call this situation *input wavelength selection*. Suitable selection mechanisms include tunable filters and optical selection switches. We use the term *output wavelength selection* when $\lambda_j$ is changed. The selection mechanisms include tunable laser sources. Further detail is given in the following section.

So that the whole WDM optical path network can be operated, administered, and managed, each function block must have a supervision function

![Generic wavelength conversion scheme](image)
for system maintenance and network survivability. The optical path network must also be designed to offer network restoration functions that can be triggered by optical layer monitoring information.

Optical path control technology will evolve from static to dynamic operation. The evolution scenario is depicted in Figure 3.26. The horizontal axis indicates the projected time when technologies required for system realization will mature, and the vertical axis represents the optical path control level in the optical path network. The deployment of simple point-to-point WDM transmission systems in the mid-1990s was the first step toward the introduction of the WDM optical path network. The next stage of development was the WDM ring network system, in which the fixed-wavelength OADM function is provided by optical filters. The development of small-scale optical switches has offered a slight degree of control flexibility in terms of OADM wavelength assignment.

Developing an OPXC system will lead the way to a higher level of optical path control in meshlike topology networks. A network operation system can ensure fast restoration or reconfiguration on a per–optical path basis, as well as providing an automatic protection mechanism for optical paths. After which, a photonic multiprotocol label switch (MPLS) router will be

![Fig. 3.26 Evolution of optical path routing control.](image-url)
developed to deal with the rapid increase in data traffic and used to build an IP-data dedicated network. The photonic MPLS router comprises parts of the OPXC and IP router, and would control each optical path autonomously according to IP data traffic. The OPXC part of the ingress photonic MPLS router sets or removes the optical path to the OPXC part of egress, based on the commands from the IP router part. In a similar way, the integrated OPXC and IP router serve as a multiprotocol lambda (wavelength) switch. An autonomously controlled network will be established when individual photonic MPLS routers are linked to each other on the plug-and-play concept.

Faster dynamic control of optical paths at the level of optical bursts or optical IP packets will be a next-generation technology. Optical path burst switching control will require optical switches that can respond faster than that for stream signal cross-connect switching. For example, switching times of the order of micro- or nanoseconds will be required.

The following section describes the system technologies of the OPXC that can support the WDM ring network system and meshlike network systems, the operation of which is based on the client–server model and/or the peer-to-peer model.

3.3.1.2. Comparison of Different Architectures

WP Cross-Connect Switch Architecture

The WP cross-connect node system architecture is simple and cost-effective compared to the VWP, although a wavelength assignment problem must be solved by the time the networks are reconfigured. This type of system is suitable for WDM optical path networks in which traffic demands are relatively static.

Two major types of system architecture are shown in Figure 3.27. In both architectures, only $M$ units of an $N \times N$ matrix switch are required to configure the WP cross-connect system. Each of the $M$ switch units corresponds to an individual wavelength and cross-connects the corresponding wavelength paths from $N$ input fiber ports to each $N$ output. The difference between Figure 3.27a and Figure 3.27b is the adoption of tunable filters and optical couplers instead of wavelength demultiplexers and multiplexers, as shown in Figure 3.27b. The $N \times N$ matrix switch can be realized by either optical or electronic technologies. When tunable filters are used instead of fixed-wavelength filters in front of an $N \times N$ matrix switch, as shown
in Figure 3.27b, the same wavelength WPs on different incoming fiber ports can be terminated at a node [13, 14]. No transmitter is depicted in Figure 3.27, so this WP cross-connect system is a transparent system, but of course transmitters could be added to create an opaque cross-connect system.

**WP/VWP Cross-Connect Switch Architecture**

Some architectures are applicable to both WP and VWP cross-connect systems, with slight modification, while yielding cross-connection in a strictly nonblocking manner. Figure 3.28 shows a cross-connect system architecture that is based on delivery and coupling switches (DC-SWs) [2, 19]. Note that the PAD function block is omitted in order to simplify the discussion. The $M \times N$ DC-SW architecture is depicted in Figure 3.28b. This $M \times N$ DC-SW allows any of the $M$ incoming optical signals to be connected to any of the $N$ outgoing fiber ports. It is possible for all channels to be cross-connected to the same $M \times 1$ optical coupler as shown in Figure 3.28b, if necessary.

Due to the switch configuration, the OPXC incoming $M \times N$ optical paths are cross-connected in a strictly nonblocking manner. Here, the network element operation system must ensure that the wavelengths of the input optical path do not collide at any of the output ports. The W/C function effectively and easily avoids wavelength collision. If the W/C function
is realized with a bit rate transparent technology, the resulting system is a transparent OPXC system. The output wavelength variable scheme suits this architecture. The addition of the W/C function simplifies the cross-connect switch scale to just $1 \times N$ for each optical path.

The WP cross-connect system can be realized easily by replacing the W/C function circuit with a WDM transmitter that has a fixed-wavelength light source. The WDM transmitter can also be removed, and the resulting transparent OPXC system would suit small-scale WP networks where regeneration is not necessary.

This system architecture offers high-link modularity and so supports the cost-effective deployment of OPXC systems at an early stage of introduction, where traffic demands may warrant only a limited equipment installation. This feature of high-link modularity is due to the architecture of the $M \times N$ DC-SW. This switch architecture is based on the requirement that the OPXC system need support only the switching of each optical path into $N$ output ports, not the $N \times M$ output fiber ports. Switching to the $N \times M$ output ports is redundant.

The parallel $\lambda$ switch–based system architecture is depicted in Figure 3.29 [15]. This switch architecture is functionally symmetrical with respect to the input and output fiber ports of the DC-SW-based system architecture shown in Figure 3.28. WDM signals on each incoming fiber are distributed.
to $M \times N$ ports with two optical coupler stages, and then signals from one incoming fiber are selected by a $N \times 1$ optical switch. Afterwards, the required wavelength (one optical path) is selected by a tunable filter and converted to some fixed wavelength by the WDM transmitter. The tunable filter and opto-electronic 3R function circuit combination can form a wavelength converter based on the input wavelength selection scheme. This system architecture supports VWP cross-connection using the W/C function circuit. This architecture also realizes strictly nonblocking cross-connection. A fixed optical filter can be implemented instead of a tunable filter for WP cross-connection.

These two types of system architecture fully utilize the WDM scheme, such that the resulting space switch scale is much smaller than the full matrix switch architecture described in the next section.

**Full Matrix Cross-Connect Switch Architecture**

The full matrix cross-connect switch architecture has a configuration such that the $(N \times M) \times (N \times M)$ port optical switch is sandwiched by
short-reach and WDM transmitters. If the transmitters were removed, this system would be a transparent WP (not VWP) cross-connect switch architecture.

Two schemes can be considered for realizing the \((N \times M) \times (N \times M)\) port count optical cross-connect switch block: a single-stage space switch and a three-stage Clos switch. The single-stage space switch is simple, as shown in Figure 3.30a. Whether or not it can be realized depends on the development of optical switch component technologies. Details of these technologies are given in Section 3.3.3.

The optical cross-connect switch based on the three-stage Clos switch architecture, which was first described by C. Clos, is shown in Figure 3.30b. It consists of \(N M \times L\) input-stage switches, \(L N \times N\) middle-stage switches, and \(N L \times M\) output-stage switches. Strictly nonblocking operation is achieved if \(L \geq 2M - 1\). For example, when designing a 16 (= \(N\)) fiber ports OPXC system in which the number of wavelengths multiplexed in one fiber is 32 (= \(M\)), then \(L\) will actually take 64 (\(\geq 63\)), and the full matrix switch port count becomes \(N \times M = 512\).

The \((N \times M) \times (N \times M)\) port optical switch block enables VWP cross-connection with the help of \((N \times M)\) WDM transmitters, where each transmitter has a fixed-wavelength light source.

### 3.3.2. OPTICAL SWITCH COMPONENT TECHNOLOGIES

#### 3.3.2.1. Space Switch Technologies

Various kinds of optical components have been developed toward realizing a sophisticated optical layer network. Among these optical components,
the optical switch has a long research history because of its importance. Optical switches have relatively simple requirements: small insertion loss, high on/off ratio, high reliability, small response time, small dimensions (including a well organized multiple-fiber wiring system).

Several mechanisms, such as polarization change, refractive index change, and beam reflection, appear to be candidates for realizing optical space switches. An optical space switch based on a liquid-crystal light-modulator array (polarization change) was studied in the first half of the 1990s [22]. It would be feasible, except for its insufficient on/off ratio and the difficulty of implementing a two-dimensional fiber array that offers an acceptably small multiple-beam coupling loss, given that the fiber arrays are spatially separated [23]. The thermo-optic or the electro-optic effect can easily induce a large change in the refractive index of a waveguide or planar lightwave circuit (PLC). Beam reflection can be realized mechanically in free space and/or a PLC. The key problem of an optical space switch based on beam steering in space is attaining low-loss beam coupling between the optical fiber arrays; the PLC switch exhibits excellent performance in this respect.

The LiNbO$_3$ Mach–Zehnder interferometer optical space switch is a PLC optical switch based on the electro-optic effect. The refractive index changes due to the application of an electric field [26]. This switch yields high-speed modulation through an applied electric field; however, the on/off ratio requirement remains insufficient. The silica-based Mach–Zehnder interferometer switch is another type of PLC switch based on the thermo-optic effect [28]. The refractive index changes due to the application of heat. This PLC thermo-optic switch (TOSW) well satisfies the requirements of small insertion loss and high on/off ratio, as described in references [19] and [28]. For example, a $1 \times 16$ matrix switch was reported to exhibit an on/off ratio of over 50 dB with an insertion loss of 3 dB [30]. In addition, the PLC-TOSW has several other excellent features, such as custom design capability, low-loss connectivity with multiple optical fibers, and high reliability. Rising and falling of a 10 to 90% edge can be attained within a switching time of approximately 2 ms. Figure 3.31 shows an example of the optical cross-connect switching operation of an $8 \times 8$ DC-SW board based on the PLC-TOSW. The PLC-TOSW is one of the most mature optical switch components among the three types of mechanisms.

Mechanical movement can switch an optical beam. Precise angle control of microreflection mirrors can control collimated beam propagation,
while mechanical shift of oil (bubble) in a fluid-containing PLC switches the optical beam through a waveguide. Micro-electro mechanical systems (MEMS) enable us to realize adequately precise micromechanical mirror angle control. The MEMS optical switch comes in two forms: a two-dimensional digital switch and a three-dimensional analog switch. Several studies have been reported. L.Y. Lin et al. [20] reported a switch chip with \(8 \times 8\) mirror elements fabricated using MEMS technology. D. T. Neilson et al. [27] reported an array with two-axis MEMS tilt mirrors. Each mirror must be controlled over tens of states for one axis if one mirror is to achieve a switching port count of over 100. In both arrangements, the micromirrors are moved by electrostatic force. Thus, the switching power is relatively low. The array with two-axis MEMS tilt mirrors would best fit the three-dimensional free space beam steering switch architecture.

A schematic view of the three-dimensional free-space beam steering switch is depicted in Figure 3.32. All the propagating beams are collimated and transit free space without any interaction. This beam steering in free space enables the number of switch elements to be minimized to two \((M \times N)\). Consequently, the free-space beam steering switch architecture is expected to be the most suitable way to build a large-dimension optical space switch fabric. However, the technologies for the steering control scheme, and those for low-loss and uniform beam coupling between the fiber arrays facing each other, are still immature. A comparison of these space switch component technologies is given in Table 3.3.
Table 3.3  Comparison of optical space switch component technologies.

<table>
<thead>
<tr>
<th>Classification</th>
<th>Characteristics</th>
<th>Features</th>
<th>Refs.</th>
</tr>
</thead>
<tbody>
<tr>
<td>Thermo-optic SW</td>
<td>Insertion loss: 6.6 dB for 16 × 16</td>
<td>Custom design capability</td>
<td>[19]</td>
</tr>
<tr>
<td></td>
<td>: 3 dB for 1 × 16</td>
<td>Reliable operation for temperature deviation and mechanical vibration</td>
<td></td>
</tr>
<tr>
<td></td>
<td>ON/OFF ratio: &gt;40 dB</td>
<td>Uniform and low loss connectivity between waveguide and fiber array</td>
<td>[29, 30]</td>
</tr>
<tr>
<td></td>
<td>Switching time: 2–3 msec</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Waveguide (PLC)</td>
<td>Insertion loss: 15dB for 16 × 16</td>
<td>Most high-speed switching</td>
<td>[26]</td>
</tr>
<tr>
<td></td>
<td>ON/OFF ratio: about 30 dB</td>
<td>Reliable operation for temperature deviation and mechanical vibration</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Switching time: &lt;μsec</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Electro-optic SW</td>
<td>Insertion loss: &lt;7 dB for 32 × 32</td>
<td>Preliminary tests of $10^4$ changes in state have produced no errors in</td>
<td>[25, 27]</td>
</tr>
<tr>
<td></td>
<td>ON/OFF ratio: &gt;50 dB</td>
<td>state</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Switching time: about 10 msec</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Insertion loss: 2–9 dB for 16 × 16</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>ON/OFF ratio: &gt;50 dB</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Switching time: 0.5 msec</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Insertion loss: 7.5 dB for 112 × 112</td>
<td></td>
<td></td>
</tr>
<tr>
<td>2-D MEMS SW</td>
<td>ON/OFF ratio: &gt;50 dB</td>
<td></td>
<td>[18]</td>
</tr>
<tr>
<td></td>
<td>Switching time: &lt;10 msec</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Insertion loss: 10 dB for 64 × 64</td>
<td></td>
<td></td>
</tr>
<tr>
<td>3-D MEMS SW</td>
<td>ON/OFF ratio: &gt;22 dB</td>
<td></td>
<td>[22, 23]</td>
</tr>
<tr>
<td></td>
<td>Switching time: no description</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Free space</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Liquid-crystal SW</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

(1) PLC: Planar lightwave circuit.
(2) MEMS: Micro-electro mechanical system.
3.3.2.2. Wavelength Conversion Technologies

The requirement for wavelength conversion in OPXC systems is that any of the optical frequencies on the frequency grid (standardized as ITU-T G.692) can be switched to any other on the same grid. The optical frequency grid is as the frequency grid with 50 GHz spacing anchored at 193.1 THz [32]. The frequency space will be narrowed in conjunction with the evolution of frequency control and WDM transmission technologies.

In the input wavelength selection scheme, one selected optical path (wavelength) is introduced into the WDM transmitter that has a fixed wavelength on the grid. The conceptual view is shown in Figure 3.33a. Wavelength selection can be realized using a selective mechanism.

Fig. 3.32 Example of 3-dimensional free space MEMS switch configuration.
One selective mechanism is the optical tunable filter; the acoustic optical tunable filter (AOTF) is a promising candidate [33]. The optical space switch is another candidate, and an \((N \times M) \times (N \times M)\) port count optical full matrix space switch has been confirmed to offer wavelength selection. In the future, the WDM transmitter can be replaced with an all-optical converter, toward realizing the transparent OPXC system.

In the output wavelength selection scheme, as shown in Figure 3.33b, the fixed wavelength of the input signal is converted into the desired output wavelength on the frequency grid. This scheme needs an optical modulator and a wavelength generator that can emit any of the optical frequencies on the grid. Candidates for the optical modulator are the LiNbO3 modulator and the fiber-to-fiber electro-absorption (EA) semiconductor modulator; both candidates are sufficiently mature. A tunable laser diode is a very simple solution for realizing a wavelength generator [34, 35]. A combination of spectral sources and wavelength selection switches is another solution [36]. All-optical modulation can be utilized. One promising technology is an optical semiconductor component employing the cross-phase modulation phenomenon in a Mach–Zehnder interferometer, as shown in
Figure 3.34 [37]. Four-wave mixing and second harmonic generation due to nonlinear phenomena also meet this functional requirement; however, there are several barriers to overcome, such as low conversion efficiency, separation of pump and input wavelengths, polarization dependency, and excessive size [38]. Several modulation technologies based on the output wavelength selection scheme are summarized in Table 3.4.

![Diagram of all-optical wavelength converter](image)

**Fig. 3.34** Example of all-optical wavelength converter. SOA, semiconductor optical amplifier.

**Table 3.4** Comparison of modulation technology based on output wavelength selection scheme.

<table>
<thead>
<tr>
<th></th>
<th>OEWC</th>
<th>XPWC</th>
<th>WMWC</th>
</tr>
</thead>
<tbody>
<tr>
<td>Waveform reshaping</td>
<td>Good</td>
<td>Moderate</td>
<td>None</td>
</tr>
<tr>
<td>performance</td>
<td></td>
<td>(No retiming)</td>
<td></td>
</tr>
<tr>
<td>Extinction ratio</td>
<td>10–20 dB</td>
<td>~10 dB</td>
<td>Proportional to input signal extinction ratio</td>
</tr>
<tr>
<td>SNR improvement</td>
<td>&gt;40 dB</td>
<td>Under study</td>
<td>Degrade</td>
</tr>
<tr>
<td>Input power</td>
<td>Over 18 dB for 2.5 Gbit/s (pin-PD)</td>
<td>3–4 dB(*)</td>
<td>?</td>
</tr>
<tr>
<td>dynamic range</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Chirp</td>
<td>Modulator dependent</td>
<td>Red or blue</td>
<td>Reversal</td>
</tr>
</tbody>
</table>

OEWC: Opto-electronic wavelength conversion  
XPWC: Cross-phase modulation wavelength conversion  
WMWC: Wavelength-mixing wavelength conversion  
(*) Depends on the pre-optical amplifier.
3.3.3. INTERFACE TECHNOLOGIES

3.3.3.1. Layered Architecture

In the design of a network system, a layered architecture is generally used to simplify the design, development, and operation of the network and to allow smooth network evolution. The layered architecture also makes it easy for each network layer to evolve independently of the others by capitalizing on the introduction of new technologies specific to each layer. Optical transport network architecture has been discussed extensively within ITU-T since 1995, and the layered architecture was first approved in February 1999 as Recommendation G.872: *Architecture of Optical Transport Networks (OTN)* [39].

The layered architecture of the optical transport network is shown in Figure 3.35. The optical transport section (OTS) is defined as the section between linear repeaters, and the optical multiplex section (OMS) is defined as the section wherein the wavelengths are multiplexed and demultiplexed. The OMS may not necessarily match the transmission link between nodes, because it could not be terminated at the regenerative repeaters if they are incorporated into the transmission link between the nodes. The linear-repeating distance between neighboring OPXC systems is limited by factors such as signal-to-noise ratio, chromatic dispersion, and the accumulation of nonlinear impairment. A regenerative repeater may be inserted into the transmission link if the linear-repeating distance is too long.

An optical channel (OCh), which is called *optical path* in this chapter, is defined for each wavelength. The OCh is terminated at the source and the sink of each trail, and the OCh trail is not disrupted until termination, even if transmitters lie along the trail. The trail termination source and sink

![Layered architecture of optical transport network.](image)
functions are generally hosted by the PAD. It is possible that several administrative domains will exist along an OCh trail. The connection between subnetworks is called a tandem connection.

### 3.3.3.2. Optical User-to-Network Interface

The OUNI is the access point to the optical path network for a client signal. A client signal is hierarchically mapped into the OCh digital frame. The hierarchical mapping procedure is shown in Figure 3.36. The client-specific overhead (OH) information is added to the client signal, and then the OCh payload unit (OPU) is formed.

A continuous bit stream signal is allowed to be mapped into the payload as a client signal. Therefore, the IP packet data should be mapped into the OPU via an SDH/SONET frame, ATM cell stream, or some frame that may be defined in the future. Figure 3.37 depicts the procedures. Even though the OTU for the GigaEther frame has not yet been defined, it may be defined in the future.

The OPU and its related OH information form an OCh data unit (ODU) frame. This ODU OH consists of information dedicated to the end-to-end ODU path and to six-level tandem-connection monitoring. The ODU is wrapped by its OH information and forward error correction (FEC) bytes,
and the OCh transport unit (OTU) is framed. For details of the OH bytes, refer to ITU-T Recommendation G.709 [40].

3.3.3.3. Optical Network-Node Interface

The ONNI defines logical functions and physical specifications for the WDM transmission system. The ONNI structure is shown in Figure 3.38. The optical transport module, order m (OTM-m) is defined as the information structure that is transported across an ONNI, where index \( m \) defines the number of supported wavelengths (i.e., the number of wavelengths...
The OCh bit rate supported by the optical transport network is the primary concern. Although bit rate transparency has been the holy grail of the research community, there are many challenges that make bit rate transparency difficult to achieve, even with the help of cutting-edge technologies. The fundamental issue is the accumulation of impairments from input to output in the optical transport network. A secondary issue is the bit rate-independent overhead information transfer scheme. The use of tone modulation has been aggressively examined for achieving the transfer of OCh overhead information without any intrusion into the payload channel [41]; however, this is not practical because tone modulation of an optical carrier modulated by the nonreturn zero code fails to achieve the signal-to-noise ratios needed to transfer overhead information. Consequently, three definite OCh bit rates have been defined as OCh transport units 1, 2, and 3 (OTU 1, 2, and 3). The bit rates are listed in Table 3.5. The optical section overhead channel, otherwise known as the optical supervisory channel (OSC), is created by using a wavelength out of the payload channel wavelength band (see Figure 3.38). The wavelength region from 1510 to 1520 nm is already being used as the OSC in actual point-to-point WDM transmission systems. An optical channel wavelength (carrier frequency) is designed to be allocated any of the grid frequencies defined as 50 GHz anchored at 193.1 THz (a wavelength of about 1552 nm). The grid frequency will narrow if higher-density WDM transmission technologies are developed that offer higher-capacity transmission.

Optical fibers potentially offer an optical frequency bandwidth of over 50 THz in the low attenuation region of under 0.35 dB/km. Within this bandwidth, the optical frequency bandwidth of about 25 THz at around

<table>
<thead>
<tr>
<th>Client Signal Type/Nominal Bitrate</th>
<th>OTU Type/Nominal Bitrate</th>
<th>Multiplication Factor (*)</th>
</tr>
</thead>
<tbody>
<tr>
<td>STM-16/2 488 320 kbit/s</td>
<td>OTU1/2 666 057.143 kbit/s</td>
<td>255/238</td>
</tr>
<tr>
<td>STM-64/9 953 280 kbit/s</td>
<td>OTU2/10 709 225.316 kbit/s</td>
<td>255/237</td>
</tr>
<tr>
<td>STM-256/39 813 120 kbit/s</td>
<td>OTU3/43 018 413.559 kbit/s</td>
<td>255/236</td>
</tr>
</tbody>
</table>

(*) OTU nominal bitrate = client signal nominal bitrate × multiplication factor.
1.55 µm appears to be feasible for long-distance transmission in the future. The optical frequency bandwidth of 25 THz is commonly divided into four bands (S, C, L, U-band) in ITU-T standardization, as shown in Figure 3.39. This frequency bandwidth (25 THz) offers 500 optical channels with a grid frequency of 50 GHz.

### 3.3.4. Fault Management and Supervision Technologies

Supervision is necessary to manage the integrity of network connections that support the trails in the optical layer network. The supervision scheme adopted for the optical transport network depends on whether or not a digital frame can be used as the optical channel. If a digital frame format is used as the optical channel, supervision schemes based on the SDH supervision concept would be preferred, given its maturity. As described in the previous section, the optical channel format has been defined by ITU-T by utilizing a digital frame, and supervision of the integrity of the optical channel connections substantially follows the SDH supervision concept. On the other hand, in OMS/OTS, some monitoring technologies have been newly developed to supervise continuity and signal quality,
because OMS needs wavelength-level multiplexing and demultiplexing mechanisms.

Monitoring the integrity of the continuity and/or transmission quality can identify the location of a failure along a trail. The detection of failures is informed toward the client layer, and necessary actions can then be carried out. Obviously, the detection of failures is important. Figure 3.40 shows a schematic of the fault-management concept in optical transport networks. Loss of signal is easy to detect in any section; however, the signal quality is not easy to measure in OMS/OTS. Several factors can cause signal quality degradation, such as optical power reflection, crosstalk, nonlinear impairment, and waveform distortion. Only bit error monitoring can directly and precisely indicate signal quality degradation. This is attained by the bit interleaved parity-8 code in the OTU. Differentiating the monitored error count data from a series of nodes can identify the fault section, as shown in Figure 3.40. Figure 3.41 shows experimental results of fault location identification. The figure presents the original bit error data measured in each node B, C, and D and differential data $S_{AB}(B-A)$, $S_{BC}(C-B)$, and $S_{CD}(D-C)$. Note that this measurement was carried out using an SDH-based optical path frame format, because the optical channel frame/format had not yet been standardized by ITU-T [16].

In OMS/OTS, optical power, optical signal-to-noise ratio, and optical carrier frequency settling error from the ITU-T-defined grid frequency are monitored for continuity and signal quality supervision. Monitoring of
these parameters can be achieved by optical spectrum analyzers. An on-board type of simplified optical spectrum analyzer has been developed for this purpose [42]. Optical layer supervision technologies are expected to advance further in the near future.

Fig. 3.41 Example of fault location identification experimental result.

References

5. CCITT, I-series Recommendations (B-ISDN), Nov. 1990.


32. ITU-T Recommendation G.692: *Optical Interfaces for Multi-channel Systems with Optical Amplifiers*.

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In this chapter, we look at optical packet-switching technologies. We begin with an overview of the general packet-switching node design. Following this, we describe the architecture design of optical packet switching with buffering strategies. Then, we look at the technologies to realize an optical packet-switching node, including subsystems, devices, and their implementations.

The chapter is organized in the following way. In Section 4.1, we describe the architecture of general packet switching and optical packet switching. In Section 4.2, we address some of the subsystems affecting the performance of optical packet-switching nodes, such as space division switches, optical buffers, and optical synchronizers. In Section 4.3, devices and implementations are discussed. In Section 4.4, we briefly describe optical burst switching, which separates relatively complex packet header processing from an optical packet-switching function. Finally, in Section 4.5, we outline some of the testbeds studied in research laboratories.

4.1. Architecture

4.1.1. GENERAL PACKET-SWITCH ARCHITECTURE

In this section, we look at the general packet-switch architecture. A block diagram representing the principle of a generic packet-switching node is
shown in Figure 4.1. The node incorporates a switching fabric and a header processor, and provides space division switching and queuing functions.

In a packet-switching node, a packet is carried from an input port to one or more output ports. An incoming packet consists of a header and a payload. The node extracts header information from a packet. A header processor in the node recognizes the header information and decides to which output port to transmit the incoming packet. The header processor sets up the switching fabric to send the payload to the destined output port (space division switching). Internal packet information is usually added to a payload to tell one packet from another. When two or more payloads arrive simultaneously at the same output port, called contention, they are temporarily queued in a buffer. The header processor regenerates a new header and adds it to the payload, then the node sends the packet to the output port.

Let us look inside a switching fabric. From the viewpoint of buffer location, there are three types of switching element architecture, as shown in Figure 4.2.

The first is an input-buffered switching element (Figure 4.2a). In this scheme, a possible contention is resolved at the input. Each input port is equipped with a dedicated buffer, and the buffer can store a packet until an arbitration mechanism directs the buffer to transmit a packet to switching media. Therefore, the switching media can carry the packet
without contentions. The buffer is achieved with first-in, first-out (FIFO) memory in the simplest way. However, an input-buffered switching element with simple FIFOs is affected by head of the line (HOL) blocking [1]. Assume that input port A and input port B each has a packet destined for the same output port X at the head of its FIFO. When an arbitration mechanism permits input port A to send a packet to output port X and prohibits input port B from sending a packet to output port X, input port B cannot send the next packet in the line, even if its destined output port is free. This HOL blocking affects throughput performance of the switching element. Many efforts have been made to resolve HOL blocking and improve switching performance, employing sophisticated buffers and arbitration algorithms [2].

The second type of switching element architecture is an output-buffered switching element (Figure 4.2b). In this scheme, a switching media can simultaneously transmit multiple packets from different input ports to the
same output port. Each output port is equipped with a dedicated buffer to avoid contention at the output port. The buffer can receive and store multiple packets at the same time; then, it transmits packets to its output port, packet by packet, in a FIFO manner. Output-buffered switching elements are simple but need high-speed switching media and buffers. Namely, they do not need both sophisticated buffers and an arbitration mechanism to avoid HOL blocking. However, it is challenging that the buffer must store the packet $N$ times faster than the input port transmission rate, when the switching element has $N$ input ports.

The third type of switching element architecture is a central-buffered switching element (Figure 4.2c). In this scheme, a buffer is shared among all input ports and output ports. Each input port stores all the packets in the central buffer, and each output port accesses the buffer in a FIFO manner. Memory utilization is more efficient than for the two other types of switching elements described previously, but the memory management of the central buffer is much more complicated.

The next section examines the architecture for optical packet-switching nodes.

### 4.1.2. OPTICAL PACKET-SWITCH ARCHITECTURE

As described in the previous section, there are three types of generic packet-switch architectures in terms of buffering. In an optical packet-switching node, buffers are usually implemented with optical fiber delay lines, because optical random access memory is not yet practical. Thus, switch architecture that requires complicated buffer management, such as a central-buffered switching element, is not suitable for optical packet switching. We describe two principal ways to achieve optical packet switching: an input-buffered optical packet switch and an output-buffered optical packet switch. If the packets are of fixed length, it is much simpler to recognize packet boundaries and implement and manage optical fiber delay line buffers. In the following description, we will assume that fixed-length packets are used.

Figure 4.3 shows an example of an input-buffered optical packet switch, which consists of optical packet buffers and an optical space division switch. For clarity, only three input/output ports and five time slots are shown. In order to avoid contention at the output of the optical switch, optical fiber delay line buffers can delay packet transmission. In this example, input port 1 and input port 2 have packets for the same output port C at
the first time slot. The packet buffer delays the first packet of input port 2 to the second time slot. The packet originally located at the second time slot must be delayed to the third time slot or later. The third and fourth time slots also conflict with the packet of input port 1. Thus, the packet originally located at the second time slot is delayed to the fifth time slot, and the first, third, and fourth time slots in input port 2 are vacant. These vacancies decrease the efficient throughput of the optical packet switch. Finally, the optical space division switch transmits all the packets to their destined output ports without contention.

Figure 4.4 shows an example of an output-buffered optical packet switch, which consists of a broadcast bus, packet buffers, and a wavelength channel selector. This architecture utilizes a wavelength-division multiplexing (WDM) output-buffering scheme [3]. A fixed wavelength channel is assigned to each input port, and the incoming optical packets are combined in a WDM manner and distributed to every output port at the broadcast bus (optical coupler). Each output port is equipped with a WDM-packet buffer. If a WDM packet incorporates two or more packets that are destined for the same output port, the packet buffer stores and duplicates the WDM packet and sends it to the WDM channel selector. The WDM channel selector screens the wanted packet out of the WDM packet. When optical switches of this type are cascaded, a wavelength conversion is necessary at each input port.

A full construction of an optical packet-switched node consists of four subblocks, as shown in Figure 4.5. An input interface consists of a header
extractor, which extracts header information from incoming packets, and a synchronizer, which aligns the incoming packets in real time against a clock. A switching core transmits the packets to their proper outputs. An output interface inserts a new header and may have to regenerate the data and convert its wavelength. A controller executes contention resolution and buffer management.
4.2. Subsystems

4.2.1. SPACE DIVISION SWITCH

An optical space division switch is one of the key subsystems in an input-buffered optical packet switch. Figure 4.6a shows an example of a space division switch for optical packet switching. It is an example of a broadcast-and-select type of switch.

The example shows a switch consisting of 256 inputs and 256 outputs. It works as follows. Two hundred fifty-six optical amplifiers, such as EDFAs (erbium-doped fiber amplifiers), amplify 256 input signals in order to maintain optical signal quality in splitting optical power. Then, the signals are split and broadcast through two hundred fifty-six 1 × 256 splitters to every 256 × 1 selector, which consists of 256 optical gates, such as SOAGs (semiconductor optical amplifier gates) [4]. The selector transmits one of the 256 input signals to an output port by turning on one optical gate among 256 gates. In this architecture, every selector can independently transmit an arbitrary input signal from among 256 input signals. Therefore, it works as an internally nonblocking crossbar switch.

Scalability is one of the most important issues for an optical packet switch. The space division switch needs 65,536 optical gates and 256 optical amplifiers for a 256 × 256 switch. In order to reduce the number of devices, WDM technologies can be applied to the space division switch.

Fig. 4.6 Broadcast-and-select switch.
The switch architecture is called a *wavelength division and space division* (WD/SD) optical switch [5].

A schematic diagram of a $256 \times 256$ WD/SD optical switch using 16 wavelength channels is shown in Figure 4.6b. On the input side, each of 256 input ports is preassigned to one of 16 wavelength channels of 16 spatial groups. Each input signal is broadcast to every $256 \times 1$ WD/SD selector via a $16 \times 1$ wavelength multiplexer ($\lambda$-MUX), an erbium-doped fiber amplifier (EDFA) to boost the optical signal strength, and a $1 \times 256$ splitter, implemented as $1 \times 16$ splitters in a two-stage tree structure. Boosting the signal strength ensures that enough optical power is distributed to each WD/SD selector. Because the EDFA simultaneously amplifies 16 signals, the number of required EDFAs is reduced to 16 ($256$ for a space division optical switch). On the output side, each output port is equipped with a WD/SD selector, which consists of 32 SOAGs (two arrays of 16 SOAGs), a $16 \times 16$ arrayed waveguide grating (AWG) router [6], and a $16 \times 1$ passive combiner.

The first-stage SOAG array of each $256 \times 1$ WD/SD selector chooses one spatial-group signal containing 16 wavelength channels. Then, the WDM signal of the chosen group is demultiplexed as it passes through an AWG router. The second-stage SOAG array selects one wavelength channel out of 16 wavelength channels. By using WDM technologies and the wavelength routing function of the AWG, the number of SOAGs required is reduced to 32 (256 for a space division optical switch), and the loss due to combining between the first-stage and the second-stage SOAG arrays is reduced by more than 12 dB. Therefore, WD/SD optical switch architecture requires only 8192 SOAGs to implement a $256 \times 256$ switch, and this number is one-eighth the amount of those used for a space division switch.

This architecture offers a strictly internally nonblocking, full-crossbar switching function, as well as a space division switch. It also supports multicasting capability. The number of input/output ports can easily be increased in terms of modularity, by adding more optical interfaces, EDFA boosters, and optical-selector packages.

### 4.2.2. OPTICAL BUFFER MEMORY

Optical buffer memory is another of the key subsystems in both input-buffered and output-buffered optical packet switches. We describe two principal ways in which the capability of buffering some packets can be incorporated into an optical packet-switching node. These two methods
are illustrated in Figure 4.7 and Figure 4.8. In both figures, we assume that time is divided into slots, represented as $T$, where each slot holds one packet.

In the parallel delay line architecture of Figure 4.7, a buffer memory is constructed using a $1 \times N$ splitter and a $1 \times N$ switch interconnected by $N$ delay lines. If each delay line can store a different number of packets—that is, the difference in propagation time through each delay line is quantized at a unit of a time slot—the buffer has a buffering capacity of $N$ packets. As we described in Section 4.1.2, if packets destined for the same output arrive simultaneously at multiple inputs in the switch element, one packet will be transmitted to its correct output, and the other packets will be stored in buffers and transmitted after $k$ time slots, according to contention resolution logic. The buffer will select a packet to propagate through a delay line of $kT$. This can be accomplished by setting $1 \times N$ switch in the appropriate state. This packet then has the opportunity to be transmitted to its desired output.

![Fig. 4.7](image1)  
**Fig. 4.7** Example of a feed-forward delay line buffer architecture.

![Fig. 4.8](image2)  
**Fig. 4.8** Example of a feed-back delay line buffer architecture.
in a subsequent slot. For example, if no packets arrive in the next slot, this stored packet can be transmitted to its desired output in the next slot.

In the looped delay line architecture of Figure 4.8, a delay line connects the output of the switch to its input. With a delay line, the switch is internally a $2 \times 2$ switch with one input from outside and one from the delay line. Again, if multiple packets contend for a single output, one of them can be transmitted and the others are stored in buffers. If the delay line has length equal to one time slot, the stored packet has an opportunity to be routed to its desired output in the next slot. If there is contention again, the stored packet, or the contending packet, can be stored for another slot in a delay line.

In the parallel delay line architecture, a packet has a fixed number of opportunities to reach its desired output. For example, in the routing node shown in Figure 4.7, the packet has at most three opportunities to be transmitted to its output: in its arriving slot and in the immediately adjacent $(N - 1)$ slots. On the other hand, in the looped delay line architecture, it appears that a packet can be stored indefinitely. This is not true in practice, because optical switches have several dB of optical loss and noise figure, so that the same packet cannot be routed through a switch more than a few times. In practice, parallel delay line architecture is preferred to looped delay line architecture because the former attenuates the signals almost equally, regardless of the path taken through the routing node. This is because almost all the loss is in passing through the switches, and in this architecture, every packet passes through the same number of switches, independent of the delay experienced. This low differential loss characteristic is important in a network because it reduces the dynamic range of the signals that must be handled.

### 4.2.3. PACKET SYNCHRONIZER

A packet synchronizer aligns packets in time slots. There are two types of synchronization to be achieved: internode synchronization and intranode synchronization. Internode synchronization compensates for the slow jitter of packets arriving at the same input. These delay variations are due to both temperature variations and chromatic dispersion resulting in different wavelengths. Intranode synchronization compensates for the delay variation of packets among input line interfaces (IINFs), output line interfaces (OINFs) and optical switching core (OSW), shown in Figure 4.5.
Figure 4.9 shows the general frame format for optical packet switching. It consists of a guard-time pattern, a synchronization bit pattern, a header, and a payload. The guard time is required to prevent optical switching from destroying payload information. The synchronization minimizes the frame overhead, such as a guard-time pattern, and maximizes the effective bandwidth. It is never realistic, however, to attempt to achieve synchronization by accurately adjusting cable length and transmission delay among packet switching nodes and in the inside of a node.

Internode synchronization can be achieved by an input packet synchronizer, referring either to the alignment of an incoming packet stream and a locally available frame clock stream or to the relative alignment of two incoming packet streams. The structure of the synchronizer is basically the same as that of a fiber delay line buffer. The difference between them is the unit of delay adjustment: namely, time slot $T$ for the buffer and $T/n$ for the synchronizer (where $n$ is adjustment resolution). Therefore, the fiber delay line length in the synchronizer is much shorter than that in the buffer.

Intranode frame alignment procedure at startup is shown in Figure 4.10 [7]. In this procedure, incoming packet streams are aligned to a frame clock supplied to the optical switching core, using both the input synchronizer and the output synchronizer. In step 1, the OSW switches different continuous patterns transmitted from the IINFs alternately. The OINFs observe the reception timing of the alternately switched patterns. In step 2, the OINFs observe the reception timing of the guard-time pattern in the frames transmitted from the IINFs. In step 3, the amount of misalignment (i.e., the difference between the reception timing of the guard-time pattern and the alternately switched pattern) is evaluated. The variable delay-line is adjusted to compensate for the misalignment. In principle, intranode frame alignment compensates for any misalignment in the range
of $+/-$ half the frame period to the accuracy within $+/-1$ resolution unit of the synchronizer. If the frame transmission timing adjusted at startup happens to drift after startup, it can be readjusted by steps 2 and 3.

### 4.2.4. BURST RECEIVER

The packet synchronizer only achieves alignment between an optical packet and a time slot, as we discussed in the previous section. When you observe the outgoing optical packet stream as a bit stream, its packet-by-packet jitter is unacceptable for a conventional optical receiver, which defines a continuous bit stream at a certain clock phase. A burst receiver properly acquires such asynchronous packets and converts them into a synchronous bit stream. This device is particularly necessary at the edge of an optical packet-switching network, because various electrical functional circuits in network elements and terminals operate with a synchronous bit stream. Such a burst receiver is required to achieve a short acquisition time within
several bits, low sensitivity penalty, high-speed operation, and high jitter rejection.

Figure 4.11 shows an example of a burst receiver. It consists of an optical-to-electronic (OE) converter, an instantaneous bit phase synchronization circuit, a serial-to-parallel (SP) converter, and a frame synchronizer composed of a frame synchronization pattern search circuit and a bit rotator [7, 8]. The instantaneous bit phase synchronization circuit is the key to success in burst receiving. The circuit provides tolerance against frame-by-frame bit phase fluctuation in the received frames. This example circuit employs four reference clocks in different sampling phases for bit phase comparison. The bit phase of the incoming frame is synchronized to the reference clock by adding proper bit delay with electrical delay lines. The bit phase synchronization is followed by serial-to-parallel conversion and frame synchronization, and then the data can be processed by downstream electrical functional circuits. With this synchronization scheme, synchronization over the optical packet switch is automatically achieved.

4.3. Device Technology

4.3.1. OPTICAL SWITCH

Various optical switching technologies are being developed, as shown in Table 4.1. Switching speed is the most important characteristic of optical switches for optical packet switching. Optical packet switching requires
switching speed in the order of nanoseconds to achieve highly efficient throughput, because longer switching time requires longer guard time and wastes the efficient bandwidth. The details of optical switching technologies can be found in reference 9. Among various optical switching devices, the semiconductor optical amplifier gate (SOAG) is one of the most practical devices for optical packet switching so far, because of a fast switching time of around 1 ns, loss compensation, high on/off ratio, and possible integration. Figure 4.12 shows the appearance of a SOAG module and its switching waveform. Integration of SOAGs is highly desirable to make an optical packet-switching node compact and cost effective.

Table 4.1  Comparison of Various Optical Switching Devices.*

<table>
<thead>
<tr>
<th></th>
<th>MEMS</th>
<th>LiNbO$_3$ EO</th>
<th>SiO$_2$</th>
<th>Polymer</th>
<th>SOA Gate</th>
<th>Bubble</th>
</tr>
</thead>
<tbody>
<tr>
<td>Switch Size</td>
<td>220 × 220</td>
<td>8 × 8</td>
<td>8 × 8</td>
<td>8 × 8</td>
<td>4 × 4</td>
<td>32 × 32</td>
</tr>
<tr>
<td>Insertion Loss (dB)</td>
<td>~5</td>
<td>~10</td>
<td>~5</td>
<td>~10</td>
<td>gain</td>
<td>~7</td>
</tr>
<tr>
<td>Crosstalk</td>
<td>&lt; −40</td>
<td>&lt; −20</td>
<td>small</td>
<td>&lt; −20</td>
<td>small</td>
<td>small</td>
</tr>
<tr>
<td>Driving Power (Voltage, Current)</td>
<td>~5 V</td>
<td>~50 V</td>
<td>~0.5 W</td>
<td>~0.5 W</td>
<td>~100 mA</td>
<td></td>
</tr>
<tr>
<td>Switching Speed</td>
<td>~ms</td>
<td>~μs</td>
<td>~ms</td>
<td>~ms</td>
<td>~ns</td>
<td>~ms</td>
</tr>
<tr>
<td>PDL (dB)</td>
<td>~0</td>
<td>~1</td>
<td>~0.5</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

*See references 10–15.

Fig. 4.12  SOAG module and its switching waveform.
4.3.2. **OPTICAL IMPLEMENTATION**

In order to make optical packet-switching technologies practical, optical implementation technologies are essential. Although optical packet-switching technologies require the implementation of a huge amount of optical components on a package, today’s optical implementation technologies based on transmission technology implement only a few or several optical components. This makes an optical packet-switching system large, complex, and quite expensive. The development of optical implementation, which implements such a huge amount of optical devices neatly into a limited space, is continuing.

Figure 4.13 shows an example of a well organized optical implementation technology [16]. This example incorporates a $256 \times 1$ wavelength division and space division (WD/SD) selector for a WD/SD optical switch, described in Section 4.2.1. In order to compact optical components into a package, 32 SOAG modules with current driver circuits and an arrayed waveguide grating (AWG) are connected by flexible optical fiber sheets and small optical connectors. The length of each optical fiber is accurately designed and engineered for this package to accommodate a large amount of optical devices.

Fig. 4.13  Example of optical implementation.
4.4. Optical Burst Switch

Optical burst switching is based on the concept of burst switching, which was proposed for voice communications in the early 1980s [17]. Burst switching is different from packet switching and circuit switching in regard to the following three characteristics:

- **Switching granularity:** A burst is an intermediate granularity between a packet and a call, which are the basic switching units in packet and circuit switching, respectively.

- **Bandwidth reservation:** A burst can be sent without an acknowledgment for a successful reservation, which is called *one-way bandwidth reservation*. In circuit switching, data can only be sent after a circuit has been established, which is called *two-way bandwidth reservation*. Two-way bandwidth results in longer latency.

- **Buffering strategy:** A burst will cut through intermediate nodes without being buffered. In packet switching, a packet is stored and forwarded at each intermediate node, which results in increased nodal complexity.

In optical packet-switching networks and optical circuit networks, data are kept in the optical domain during switching to lessen electronic processing and switching bottlenecks, and to achieve transparency to bit rates, protocols, and coding formats. For instance, optical circuit switching in WDM networks establishes lightpaths before data can be transmitted, whereas optical packet switching normally uses optical buffers made of fiber delay lines to switch fixed-length packets synchronously.

Optical burst switching has been proposed as an optical switching paradigm to combine the best of optical circuit and packet switching while avoiding their shortcomings [18, 19, 20, 21]. Optical burst switching can provide improvements over optical circuit switching in terms of bandwidth efficiency and network scalability via statistical multiplexing of bursts. An example of an optical burst-switching node is shown in Figure 4.14. Optical buffers can be eliminated, because an optical burst-switching node sends a control packet carrying routing information on a separate control channel and reserves bandwidth before the transmission of the corresponding burst. Therefore, optical burst switching can reduce the nodal complexity of optical packet switching.
4.5. Optical Packet-Switching Testbeds

4.5.1. NEC TESTBED

Recently, researchers at NEC demonstrated the ultralarge-scale opto-electronic packet switching system, which is called photonic core node (PCN) or the terabit/s throughput opto-electronic ATM switch (TAOS) [5, 16]. The concept of PCN is that it accommodates the optical cross-connecting function and/or the IP core routing/ATM core switching function simultaneously, sharing the opto-electronic packet-switching fabric. The optical cross-connecting function is realized by simply connecting the WDM transponders to the opto-electronic switching fabric. An IP routing/ATM switching function requires data buffering and contention-resolution logic, for which the optics has not yet matured. To implement an IP routing/ATM switching function, an opto-electronic switching fabric should be used as the juncture switch for expanding the capacity of the ATM switches and IP routers. Therefore, in PCN, data buffering is performed using electronic buffers in each switch and router. The contention-resolution logic is performed by an electronic switch controller, which resolves traffic contention among switches and routers.
The first prototype of PCN consists of a crossbar-equivalent opto-electronic switching fabric based on WD/SD optical switch architecture, packet synchronizers, and burst receivers previously discussed in this chapter. Figure 4.15 shows the appearance and configuration of an NEC testbed. There are two cabinets. One is for a PCN prototype, which has $2 \times 2$ WD/SD opto-electronic switching fabric, a $4 \times 4$ packet scheduler, and two packet buffers. The other is for an ATM cell multiplexer as an interface for ATM networks. The interface speed between PCN and the cell multiplexer was set to 5 Gb/s, obeying the cell multiplexer’s clock speed. The switching

![Fig. 4.15 Appearance and a block diagram of an NEC testbed.](image-url)
fabric itself is upgradable up to 2.56 Tb/s; the number of ports is expandable up to $256 \times 256$, and each port can be operated at 10 Gb/s.

4.5.2. **NTT TESTBED**

This testbed was developed in NTT Network Innovation Laboratories in 2000 [3]. The switch architecture is based on a broadcast-and-select WDM output-buffered switching element, as previously shown in Figure 4.4. The testbed is equipped with three optical packet senders, one WDM output buffer, one optical packet receiver, and electrical control circuits, such as a buffer controller, in one cabinet. The switching capacity of the system can be expanded up to 320 Gb/s; 32 wavelength channels operated at 10 Gb/s. Thirty-two channel wavelength selectors were developed for this testbed using hybrid-integrated planar lightwave circuit (PLC) technologies.

4.6. **Summary**

Optical packet switching offers the potential to achieve much higher capacities for packet-switched networks than may be possible with electronic packet-switched networks. However, significant advances in technology are required to make them practical, and there are some significant barriers to break through, such as the lack of economical optical buffering and the difficulty of propagating very high-speed signals at tens and hundreds of Gb/s over any significant distances of optical fiber. There is a need for compact and economical optical switching matrices. At this time, semiconductor optical amplifier gates achieve fast optical switching; however, these have relatively high polarization-dependent losses and saturation of input/output signal power. In addition, integration of optical gates is essential to fabricate economical large switches. Temperature dependence of individual components can also be a significant problem when multiplexing, demultiplexing, or synchronizing signals at such high bit rates. Although all of these challenges remain, it is expected that a wide range of solutions will emerge to meet them.

**References**


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5.1. Outline

Submarine cable systems have been used as international telecommunication media interconnecting the continents, and as domestic or regional communication media for countries facing or surrounded by the sea. Submarine cable systems have been constructed by telecommunication carriers in accordance with predictions of traffic demand. In the late 1990s, worldwide deregulation occurred, and telecommunication industries produced many new submarine operators and users in the telecommunication industries. At the same time, there was an unprecedented international traffic increase, fueled by the Internet and by the introduction of DWDM fiber-optic technologies. These changes altered submarine cable systems considerably, especially their network aspect.

This chapter highlights the network technologies of the submarine cable systems that use optical amplifier technologies. First, the elements used in optical amplifier submarine cable networks are reviewed to allow understanding of actual system implementation. Next, the network technologies are described, featuring the transoceanic self-healing ring widely deployed in current submarine systems. Finally, the future of submarine network architectures is discussed.
5.2. Progress of Optical Submarine Networks

The initial optical submarine cable systems were deployed at the end of the 1980s. The first-generation transoceanic systems, applied to TPC-3 and TAT-8, used 1.3 μm wavelength range optical regenerative repeater technologies working at 280 Mb/s. TPC-3 and TAT-8 could connect three landing points through submerged branching units by separating fiber pairs under water, whereas the previous coaxial submarine system, in principle, could not be branched and could not connect multiple points [1, 2]. At the beginning of the 1990s, the second-generation regenerator systems, using a 1.5 μm wavelength range optical regenerator working at 560 Mb/s, were deployed with installations of TPC-4, TAT-9, and TAT-10 [3, 4]. TAT-9 connected the three landing stations of the U.S., the U.K., and France on a time slot basis, using the undersea branching multiplexer (UBM).

In 1995, the introduction of erbium-doped fiber amplifier (EDFA) technology to the submarine cable system greatly increased cable capacity. Figure 5.1 shows the capacity increase per fiber pair for commercial submarine cable systems. The first transoceanic optical amplifier systems of TPC-5 CN and TAT-12/13 were completed in 1996 in the Pacific Ocean and the Atlantic Ocean, respectively [5, 6]. Combining SDH technologies,
optical amplifier submarine systems have significantly progressed in terms of the network manageability. The first adoption of self-healing SDH ring networks to TPC-5 CN and TAT-12/13 improved system quality and reliability. In addition, connecting multiple submarine segments with SDH linear ADM equipment at the cable landing stations established large-scale submarine networks. With this architecture, FLAG cable connected 17 countries from Europe to Asia [7]. The addition of wavelength-division multiplexing (WDM) technologies augmented the network flexibility and sophistication of submarine cable systems. Namely, wavelength-based node connection extended logical connectivity. In the China–U.S. cable, multiple WDM self-healing rings could be established by allocating protection capacity to the spare wavelengths [8]. Using the submerged color branching unit, the wavelength-based connection among the cable landing stations could be established in SEA-ME-WE 3 cable.

In the initially deployed WDM submarine cables, four to eight WDM at 2.5 Gb/s systems were applied. In second-generation WDM systems, such as the Japan–U.S. cable, Pacific Crossing-1 cable, and TAT-14, 16 WDM at 10 Gb/s systems were used [9]. The enhancement of WDM technology enables 32 WDM, 64 WDM, 96 WDM, and 128 WDM at 10 Gb/s [10]. This enhanced WDM version of DWDM technology drastically improves the unit capacity cost of the submarine cable system. Meanwhile, the large international data traffic demand, due to the explosion of Internet traffic, yielded a new submarine cable business model and raised the strong requirement of multiple node connectivity. The liberalization of telecommunication enables new operators and users to enter the submarine cable industries. In addition, venture-capitalized private companies and existing carriers alike can deliver wholesale services of submarine capacity to end users, such as Internet service providers (ISPs) and application service providers (ASPs).

As shown in Figure 5.2, the privatizations of the submarine cable systems are increasing from the late 1990s by the prosperities of such carrier’s carrier enterprise, although the first private submarine cable of PTAT was constructed in 1989. Although in the previous consortium cables, IRU-based capacity sales were mandatory, the leased-line or on-demand based capacity sales in private cables can expand the number of the submarine cable users at the same time that legislative regulation of data communication businesses decreases. Figure 5.3 and Figure 5.4 show optical amplifier submarine cable networks deployed in the Pacific and Atlantic oceans, respectively.
<table>
<thead>
<tr>
<th>Region</th>
<th>Cables</th>
<th>Ready For Service Date</th>
</tr>
</thead>
<tbody>
<tr>
<td>Atlantic</td>
<td>TAT-8, TAT-9/10, TAT-11, TAT-12/13, Colombus 2, Colombus 3, TAT 14, Gemini, AC-1, AC-2 Yellow, FLAG-Atlantic</td>
<td>1990, 1995, 2000</td>
</tr>
<tr>
<td>Central/South America</td>
<td>TPC-3, TPC-4, TPC-5, Americas 1, PanAm, Atlantis-2, MAYA-1, Americas 2, SAC, MAC</td>
<td>1990, 1995, 2000</td>
</tr>
</tbody>
</table>

**Fig. 5.2** Optical submarine cable systems in the world.

**Fig. 5.3** Optical amplifier submarine cable networks in the Pacific Ocean.
To deliver services to end users, connectivity from city to city and global viability are required in submarine networks, because the ISP points of presence to aggregate the local traffic are located in metropolitan areas. To satisfy this requirement, the network architecture must be reengineered from the architecture for the previous consortium submarine cables, which were connected to their own existing terrestrial systems at the cable landing stations. The new submarine system operators have constructed the submarine networks integrated with the terrestrial back-hauls, procuring dark fibers to remove the complexity of multiple segregated network administrations for such connections.

On the other hand, the consortium cables attempted to share the submarine cable capacity by administering fiber pair separately and by integrating the fiber pair with each company’s own terrestrial backbone network. In both cases, the network must be designed so that the submarine networks and the terrestrial networks are monolithically integrated.

The traffic shift from voice to data will also change the network architecture. In terms of network protection, voice-oriented networks
required a fast protection time to avoid dropping calls. For this purpose, self-healing rings, which furnish the SDH-based transoceanic protocol, have been widely deployed in submarine cable networks, where the extra and deterministic protection capacity is needed. For data transport, however, such fast protection time is not necessarily required. In the next-generation submarine system, a more sophisticated network architecture of mesh networks is expected to be deployed in submarine networks, when the major traffic carried by the submarine cables becomes data.

5.3. Submarine Cable Systems Configuration

5.3.1. SUBMERGED PLANT

Figure 5.5 shows the typical configuration of an optical amplifier submarine cable system using a submerged branching unit (BU). The submerged optical cable contains multiple fiber pairs. In accordance with the number of fiber pairs, the submerged optical repeaters accommodate the same number of subsystems, which enable bidirectional transmission with the two
different directional optical amplifiers. The electrical power for the operation of the repeater is supplied by the power-feeding equipment (PFE) with direct current from the shore-end landing station through the metallic conductor in the submerged cable, which is insulated against sea water.

5.3.1.1. Optical Submarine Cable

Figure 5.6 shows a cross-sectional view of the optical submarine cable of lightweight (LW) cable, used for deep water up to 8000 m [11]. For shallow water of less than 1000 m, armored cable is used. Armored cable is protected by thick steel wires wound around the LW cable. Optical submarine cables, for example, accommodate up to eight fiber pairs [12].

Optical fibers are stranded around a copper-clad steel wire as the unit tension member embedded in UV-cured resin to form a cylindrical fiber unit. Water ingress into the cable is prevented by this resin. The fiber unit is placed in the center of the cable longitudinally.

![Fig. 5.6 Structure of optical submarine cable.](image-url)
5.3.1.2. Optical Submarine Repeater

Figure 5.7 shows a block diagram of the subsystem unit of the submerged optical amplifier repeater [13]. The optical amplifier repeater boosts the optical signal to the specified power level. The repeater subunit providing bidirectional amplification consists of an optical amplifier pair, an optical pumping unit, and a supervisory circuit. The repeater has no high-speed electrical circuits and is configured in a very simple architecture, which enhances reliability and functional robustness. The pump power is coupled into the EDF through a WDM coupler designed for optimal performance of signal band and 980 nm for the transmission path and pump path, respectively. The optical isolator prevents growth of backward-propagating optical power along the optical fiber. The monitor couplers are used for the input and output power monitoring system. The gain equalizer (GEQ) is required to obtain a flattened gain shape throughout the system. Figure 5.8 shows the optical spectrum of a 96 WDM signal after 7500 km transmission through cascaded optical amplifier repeaters with the gain equalizer.

Multiple optical amplifier repeater units are accommodated in the pressure housing. The operation of each amplifier pair is independent of the components used to implement the other amplifier pairs in a repeater.

Fig. 5.7 High-level block diagram of an optical amplifier repeater.
The repeater housing is connected to the submarine cable by the cable coupling. The status of the repeater located at the sea bottom can be supervised remotely through the repeater supervisory circuit in in-service condition. In out-of-service condition, the optical power level can be measured directly through a coherent OTDR test set, through the permanent loop-back path furnished in the amplifier [14].

5.3.1.3. Submerged Branching Unit (BU)

In terms of signal branching in the water, a submerged branching unit is employed as indicated in Figure 5.5 [15]. Figure 5.9 shows the BU with cable coupling (upper) and the structure of the housing unit (lower). The BU housing is designed based on the same concept of submersible repeaters. The mechanical structure is designed to withstand any stress experienced in laying and recovering at depths up to 7000 m. In the branching unit, the fiber pair is branched inside, together with the electrical power-switching function, for the reconfiguration of power feeding in the event of a cable failure. In WDM systems, color-branching units have also been developed. A color-branching unit adds and drops the specific color with fixed band-pass optical filters.

The electrical power-switching circuit of the BU is designed to have the capability of power reconfiguration in the case of a network fault. Figure 5.10 shows a power-switching circuit that has been used in a trunk-and-branch submarine cable network. Each power path configuration is
Fig. 5.9  Mechanical structure of a branching unit.

Fig. 5.10  Power-switching circuit of a BU.
controlled by a power-switching circuit consisting of vacuum relays, Zener diodes, and resistances. The vacuum relay denoted as \( K \) is activated by the current from the station. When power feeding is established between Station A and Station B, the branch cable connected with Station C will be grounded under the activation of K1 and K4 relays. Relay K4 is for a self-holding circuit of the branch leg, to avoid unstable switching in the event of a cable fault in the trunk cable. When a fault in the cable connected to Station B occurs, reconfiguration can establish power feeding between Station A and Station C.

Figure 5.11 illustrates the BU power-switching configurations for (a) no power, (b) normal operation, and (c, d) cable fault conditions. Each power path switching configuration is established by the powering procedures among the PFEs in the cable stations.

### 5.3.2. STATION EQUIPMENT

In the shore-end cable landing station, several kinds of equipment are used, as shown in Figure 5.12. They can be categorized in terms of function:

- Submarine line terminating equipment (SLTE)
- System interconnection equipment (SIE)
- Power feeding equipment (PFE)
- Line monitoring equipment (LME) for submerged plant supervision
- Element management system (EMS) for SIE

The maintenance controller (MC) is the element management system dedicated to the submerged equipment. MC and EMS for SIE are interconnected to the network management system (NMS) for network operation, administration, maintenance, and provision (OAM&P). In addition, the network clock source is provided through SIE from DCS. For network synchronization, a high-precision clock conforming to Stratum 3 is usually employed.

SIE provides the network function within the submarine cable systems and interconnection to other networks of domestic networks or backhaul systems. Major functions of SIE are multiplexing/de-multiplexing, add/drop, protection/restoration, and cross-connection in time slot plane. To provide these functions, standard SDH/SONET equipment is widely employed. However, for fast ring protection, SDH equipment specifically standardized for submarine application has been developed.
5.3.2.1. Submarine Line Terminating Equipment (SLTE)

SLTE was designed to transport the WDM capacity through the submerged cable system. SLTE consists of line termination unit (LTU), wavelength terminating unit (WTU), and dispersion equalization unit (EQU), if required. LTU for SLTE was developed to transport STM-16 and STM-64 signals with WDM wavelengths determined by the bandwidth of the submerged optical amplifier repeater. WTU multiplexes and demultiplexes WDM optical signals for LTUs. EQU compensates for the accumulated chromatic dispersion for each wavelength. Figure 5.13 shows the SLTE configuration of a 96 WDM system. Figure 5.14 shows WTU and LTU bays for SLTE. Using high-density packaging, the LTU bay can accommodate four to eight transmitter/receiver shelves.

Fig. 5.13 WTU and LTU for SLTE.
LTU furnishes an FEC coder/decoder to improve error performance by correcting errors [16]. The FEC used in the LTU is an 8 byte, error-correctable 255 byte code length Reed–Solomon code of RS (239, 255) [17]. Figure 5.15 shows the FEC frame defined at 10 Gb/s. The 10 Gb/s signal is byte-interleaved to 512 subframes with a 19 Mb/s signal speed by serial-to-parallel circuit. In order to add 1 bit overhead in each subframe and the FEC bytes, the data rate is converted from 19 Mb/s to 21 Mb/s. The FEC overhead information is inserted into each 21 Mb/s subframe signal. The FEC overhead is used as an OAM function for SLTE, together with the frame synchronization. The subframe is coded by a Reed–Solomon coder, adding 16 redundant bytes. Encoded subframes are multiplexed into a 10.664228 Gb/s line signal [18].

The received line signal is demultiplexed to the subframe. FEC decoders perform the error correction for the subframes at 21 Mb/s and report the error counting. Figure 5.16 shows the error-correcting performance. The FEC error-correcting information is transformed into performance data and reported to the element management system (EMS). The FEC overhead digital communication channels are used for the order wire and the data communication to SLTE in other landing stations. In Figure 5.16, the
### Fig. 5.15 FEC frame structure.

<table>
<thead>
<tr>
<th>Overhead</th>
<th>Data</th>
<th>Redundant</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>239</td>
<td>240 255</td>
</tr>
<tr>
<td>sub-frame 1</td>
<td></td>
<td></td>
</tr>
<tr>
<td>sub-frame 2</td>
<td></td>
<td></td>
</tr>
<tr>
<td>sub-frame 3</td>
<td></td>
<td></td>
</tr>
<tr>
<td>sub-frame 4</td>
<td></td>
<td></td>
</tr>
<tr>
<td>sub-frame 5</td>
<td></td>
<td></td>
</tr>
<tr>
<td>sub-frame 6</td>
<td></td>
<td></td>
</tr>
<tr>
<td>sub-frame 7</td>
<td></td>
<td></td>
</tr>
<tr>
<td>sub-frame 8</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

### Fig. 5.16 Error-correcting performance of SLTE.

Corrected BER vs. Line BER for different error-correcting schemes:
- **Without FEC**
- **Concatenated FEC**: RS(255, 239) + RS(239, 223)
- **ITU-T G.975**: RS(255, 239)
performance of enhanced FEC using concatenated RS block codes is also shown.

When a failure alarm is detected in the incoming signal, LTU sends an alternate maintenance signal (AMS) instead of an STM-N tributary signal to indicate the alarm to the equipment downstream. For the loss of the tributary signal at the LTU, the LTU at the far end generates an AMS signal on the tributary side in the same fashion. Figure 5.17 shows the AMS indication for an incoming tributary signal failure. The AMS signal activates the protection mechanism of SIE and notifies the EMS.

5.3.2.2. Power Feeding Equipment

The power feeding equipment (PFE) is installed at the cable station to supply a precisely controlled constant direct current of about 1 A to submerged optical repeaters through the optical cable conductor together with the sea ground. PFE can convert −48 V station voltage to high voltage in order to drive several hundred repeaters in a transoceanic system. The power-feeding system depends on the cable length and topology. Figure 5.18 shows a typical block diagram for a double-end power-feeding configuration. For a transoceanic system, a power-feeding configuration with redundant PFE is employed to reduce the voltage and to meet the outage requirement.
When a cable landing station is close to the beach, the submarine cable may be brought directly into the cable station. In that case, the cable terminating box (CTB) is used in the station to terminate and to separate the optical fiber pairs from the power conductor of the submarine cable. Otherwise, the submarine cable is terminated in the land joint box (LJB), which is installed in the beach manhole (BMH). The optical fibers of the submarine cable are separated from the power conductor. The power feeding line is connected to the SW bay, and the optical fibers are spliced with interoffice optical fibers.

The PFE consists of a power regulator (PR) bay, power monitor (PM) bay, load transfer (LT) bay, test load (TL) bay, and switch (SW) bay. The number of PR and TL bays are determined by voltage required for the applied system. The PR and PM bays convert the $-48$ V DC station battery voltage into a precisely regulated, high-voltage constant-current output. PFE bays, namely PR, PM, LT, TL, and SW bays are designed for conversion, regulation, protection, and monitoring of the voltage. In order to achieve high reliability, no forced cooling is used, except for the test load.
5.3.2.3. Network Management Equipment

Because TMN architecture has been widely employed in the field of telecommunications for network operation, submarine cable systems were designed based on the TMN network management system. TMN architecture was established by ITU-T in 1994 to provide high-quality service and to minimize the cost of service development and telecommunication services. TMN architecture defines the functions of five layers for telecommunications network management:

- **Business management layer**: Defines functions related to the management of customer services
- **Service management layer**: Defines functions related to tariffs, provision management, etc.
- **Network management layer**: Defines functions related to routing, traffic, restoration management, etc.
- **Network element management layer**: Defines functions for individual element management, such as network switching system management, transmission system management, etc.,
- **Network element layer**: Defines functions for telecommunications equipment

Current submarine cable networks conform to the TMN architecture from the network element level to the network management level. Figure 5.19 shows the configuration of the submarine cable network management system. The submarine cable system is interconnected with the terrestrial SDH transmission system through SDH tributaries of the STM-N interface. The add/drop multiplexer (ADM) multiplexes and demultiplexes at STM-1 level for STM-16 or STM-64 signals and also furnishes the self-healing function. The ADM’s furnishing of the self-healing ring function is referred as network protection equipment (NPE). Other equipment—SLTE, PFE, and LME—supports the submerged transmission facilities.

SLTE, PFE, LME, and NPE are defined as network elements (NEs) in the network element layer. NEs for submerged transmission facilities are monitored and controlled by the maintenance controller (MC). NPE is managed by network management equipment (NME). MC and NME are defined as the element management system (EMS) in the network element management layer. The MC supervises station equipment at the element management level through TMN interfaces and sends alarms in the event of an NE failure.
Both NEs and EMSes are collocated in the cable station and controlled by the cable station operators. NEs and EMSes are connected to a local area network (LAN) with a Q3 interface; equipment alarms and performance data will be monitored by EMSes. They are also remotely controlled by the remote MC and NME installed in the network operations center (NOC) located in the central office of the metropolitan area.

The network management system (NMS) is defined in the network management layer. The NMS provides the centralized management capability through a WAN using the DCN of the submarine cable network. Master cable stations are remotely monitored and operated by the remote EMSes or NMS in the NOC. To avoid network management failure, redundant network management is arranged by furnishing the same architecture in the slave cable station.

5.4. Network Configuration

The submarine cable system previously functioned as the point-to-point transmission medium for connecting a few landing stations on
different continents. In the past ten years, as fiber optic networks have been deployed in terrestrial cable communication systems and an international standardized digital hierarchy has been introduced, submarine cable systems have been changed to interconnect terrestrial networks through a multitude of landing stations. In addition, network restoration within submarine cable systems has become more important due to the increase of submarine cable capacity, which cannot be restored by the capacity of a satellite link and which conforms to the requirement of fast restoration. Recent submarine cable network architectures have been optimized by network planners in various forms, in accordance with diverse conditions and requirements, such as traffic patterns, connectivity, geography, availability, economics, sovereignty among countries, etc. In some cases, the networks contain the terrestrial crossing segments for physical or political reasons.

Typical network topologies deployed in the past several years are ring, trunk-and-branch, festoon, and mesh, although individual networks vary significantly. A specific network may be a hybrid of these network topologies: logical ring networks in the trunk-and-branch physical topology, etc. To understand which topology is optimal for each requirement, the features of the submarine networks will be discussed, addressing typical network architectures.

5.4.1. RING NETWORKS

The self-healing ring network connects multiple landing station nodes by the submarine cable as a loop. Figure 5.20 shows the four-nodes ring network configuration. In a cable, the protection capacity is reserved by allocating half of the fiber pairs for protection use. Working capacity is completely restored by routing the traffic in the reverse direction with the protection capacity through the self-healing fast restoration protocol [19]. Especially in the transoceanic submarine cables carrying a large amount of traffic between continents, this fast protection is strongly required to minimize protection time. For the self-healing function, SDH/SONET ring protection is utilized. However, the four-fiber bidirectional line-switching ring protocol used in SONET rings may cause excessive delays due to a triple transoceanic crossing protection route. Thanks to the transoceanic ring protocol, several hundred milliseconds of protection switching time are attained, including the transmission delay due to the transoceanic distance. This enables the elimination of dropped calls in the event of
cable failure. This protocol was modified by implementing head-end switching at switching nodes to eliminate such delays, together with the use of protection capacity on a preemptive basis. Examples of this switching mechanism are shown in Section 5.5.

Half of the cable capacity is dedicated to protection or used on a preemptive basis. In network planning, system economy is also taken into account when adopting a ring network architecture, because the unit service capacity cost becomes higher due to the excessive capacity required.

For alternative protection, path switching can be utilized in the ring network architecture. Path switching requires two different dedicated paths between head-end and tail-end to bridge the traffic to two paths at the head-end. In the event of a failure, the tail-end switch is only executed to protect the traffic. Accordingly, 50 ms of fast protection switching time is achievable, although preemptive traffic is not available.

Ring network architecture can be logically formed in other network topologies, although some failures may occur in the protection. For example, in trunk-and-branch networks (explained in the next section), the collapsed ring can be configured by connecting the fiber pairs through network protection equipment as a loop, as shown in Figure 5.21. However, in this architecture, the cable cut in the trunk line cannot be protected, whereas
in the event of a failure in the branch link, the traffic in the trunk line is protected. The traffic dropped or uploaded in the failed branch, however, is not protected. To protect the traffic in the branch link, double-branch topology can be implemented. Figure 5.22 shows the double branch arrangement.

![Collapsed ring](image1)

**Fig. 5.21** Collapsed ring.

![Collapsed ring and redundant branching arrangement](image2)

**Fig. 5.22** Collapsed ring and redundant branching arrangement.
5.4.2. **TRUNK-AND-BRANCH NETWORKS**

In coastal submarine systems sometimes found linking islands, trunk-and-branch networks are often deployed [20]. Figure 5.23 shows a typical trunk-and-branch topology. To branch the capacity from the trunk line, fiber pair branching or color branching in a WDM system is utilized through the submersible branching unit. The branching system allows branching of partial capacity from full cable capacity. This improves system economy by saving the facility of the capacity termination at the landing stations connected to the trunk line through the branching unit. Network survivability can be improved by adopting the collapsed ring network architecture, as addressed in the previous section. As another advantage, the branching unit with stub cable can be preinstalled for the non-initial parties whose landing station will be financed at a later stage, as indicated in Figure 5.23.

On the other hand, the drawback of this architecture is that the fiber pairs contained in the trunk line often become longer spans. This results in shortening the repeater spacing and increasing the system cost. To balance network survivability with system cost, the length of the trunk line fiber pairs is optimized.

![Fig. 5.23 Trunk-and-branch network.](image-url)
5.4.3. **FESTOON NETWORKS**

Festoon networks are often deployed in coastal submarine systems. Festoon networks directly link landing stations by submarine cables. Figure 5.24 shows the festoon network topology. When the distance between landing stations is short, nonrepeated cable can be employed. In such a system, system economy is much improved. Namely, power-feeding equipment is not required, and submersible cables are less expensive. For the system, however, the terminal equipment terminating the cable capacity may affect the system cost when the cable capacity is much increased.

This network architecture has a very low protection mechanism because it has less connectivity. In the event of a cable cut or station failure, no internal protection route is available. In addition, in shallow water, the submersible cable is vulnerable to fish activity and natural disasters. To preserve network survivability, terrestrial links or additional submersible segments will be required.

5.4.4. **MESH NETWORKS**

Ring network architecture has excellent features in terms of network survivability, whereas the overbuild capacity for dedicated protection remains a problem in terms of cost effectiveness. To improve cost effectiveness, network architecture that shares protection capacity has recently attracted attention. By adding a segment across the ring, as shown in Figure 5.25, the capacity carried in such a segment is protected by the original ring
network capacity. In other words, 1:N mesh protection is achieved. This network architecture improves the protection capacity. This type of network architecture is deployed in the Atlantic Crossing cable networks (AC-1 and AC-2).

5.5. Network Implementation

5.5.1. TRANSOCEANIC RING NETWORK PROTECTION

Ring network protection was originally optimized for channels at the AU-4 level in the multiplex section of an SDH frame. The channels are defined to connect different source and destination nodes with traffic paths. The channel can be concatenated of multiple AU-4 tributaries. In ring networks for submarine cable systems, in order to balance the delay due to the propagation distance for incoming and outgoing signals, a bidirectional switched ring is used. In accordance with the requirement for protection time, line-switched or path-switched rings are selected, as explained in Section 5.4.
In terms of capacity utilization efficiency, the multiplex section (MS) shared protection achievable in a line-switched ring is used. In MS-shared protection rings (MS-SPRING), the protection channels can be used as extra capacity on a preemptive basis and shared by the failed working channels in the span base. For example, when all traffic is destined for the adjacent node only, total capacity can exceed the span capacity, whereas the maximum capacity for path-switched rings is limited by the span capacity.

MS-SPRING can be also categorized into two types: two-fiber and four-fiber. Two-fiber MS switched rings require only two fibers for each span of the ring. Each fiber carries both working channels and protection channels. But two-fiber MS-SPRINGs support ring switching only. Four-fiber MS-SPRINGs require four fibers for each span of the ring. The working and protection channels are carried on separate fibers. Four-fiber MS-SPRINGs can support span switching as well as ring switching.

Figure 5.26 illustrates protection using span switching for unidirectional or bidirectional failure on a working channel between node A and node B.

![Figure 5.26 Span switch in a four-fiber MS-SPRING.](image-url)
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Working traffic is protected by the protection fiber, similar to a 1:1 protected linear system, between node A and node B.

Figure 5.27 illustrates protection using ring switching for a cable cut failure between node A and node B. Ring switches are established at the two nodes adjacent to the cable failure. These ring switches loop back the working channels to and from the protection channels, such that the protection channels unaffected by the failure are used to restore the failed span. In this protection mechanism, however, the restoration route crosses the ocean three times when the spans between A and D and between B and C have transoceanic distances. The propagation delay due to the triple ocean crossing degrades system performance. The problem becomes serious when the distance between nodes exceeds 1500 km.

![Figure 5.27 Ring switch in a four-fiber MS-SPRING.](image_url)
Figure 5.28 illustrates the restoration route for the transoceanic ring network. For example, the working channel affected by the failure between node A and node C is switched to its original drop point. In the transoceanic approach, all nodes are allowed to switch in conjunction with ring maps, which indicate the channel allocation for the network. The transoceanic protection mechanism eliminates excessive delay due to the triple ocean crossing, as shown in Figure 5.28.

Because only the affected AU-4 tributaries are switched for the transoceanic ring network, the preempted extra traffic can be reestablished on the protection channels not used to restore the working channels.

An automatic protection switching (APS) protocol is used to activate the switch at the SDH node. The ring APS protocol is carried on the K1 and K2 bytes in the multiplex section overhead. In the case of a four-fiber ring,
the APS protocol is only active on the fibers carrying protection channels. Functions required in real time to make a protection switch use K1 and K2 bytes. Additional functions supporting the APS protocol, but not required in real-time fashion, use the DCC (e.g., restoring the part-time traffic after a switch).

Figure 5.29 shows the functions of bytes K1 and K2. Bits 1–4 of the K1 byte carry bridge request codes, which contain information such as signal failure, signal degradation, and acknowledgment of bridge request. Bits 5–8 of the K1 byte carry destination node identification. Bits 1–4 of the K2 byte carry source node identification. Bit 5 of the K2 byte indicates a short-path or long-path code, along which messages are transmitted. Bits 6–8 of the K2 byte carry status codes, which contain information on the source node, such as bridge state or switching state. Because node identification codes use four bits, a ring accommodates a maximum of 16 nodes.

Figure 5.30 shows the sequence of protection actions in the case of a unidirectional signal failure. In this example, a failure occurs in a working fiber from node D to node A. Node A detects a signal failure condition on its

<table>
<thead>
<tr>
<th>Bridge request code</th>
<th>Destination node identification</th>
</tr>
</thead>
<tbody>
<tr>
<td>Bit 1</td>
<td>Bit 2</td>
</tr>
<tr>
<td>0000</td>
<td>No request</td>
</tr>
<tr>
<td>1100</td>
<td>Signal fail (Span) SF-S</td>
</tr>
<tr>
<td>1011</td>
<td>Signal fail (Ring) SF-R</td>
</tr>
<tr>
<td>0010</td>
<td>Reverse request (Span) RR-S</td>
</tr>
<tr>
<td>0001</td>
<td>Reverse request (Ring) RR-R</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Source node identification</th>
<th>Long/Short</th>
<th>Status</th>
</tr>
</thead>
<tbody>
<tr>
<td>Bit 1</td>
<td>Bit 2</td>
<td>Bit 3</td>
</tr>
<tr>
<td>Source node ID is set to the node's own ID.</td>
<td>0 = short-path code (S)</td>
<td>1 = long-path code (L)</td>
</tr>
<tr>
<td>001 Bridge (Br)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>010 Bridge and switched (Br&amp;Sw)</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

**Fig. 5.29** Major functions of bytes K1 and K2.
working channels from node D. It sends an SF-S request message to node D along both the short and the long paths. Receiving this request, node B and node C on the long path enter the K-byte pass-through state. They do not change path connections. Upon receiving the message from node A on the short path, node D executes a bridge action; identical traffic is transmitted on both working and protection fibers. Node D sends a reverse request on the short path and informs node A that it has received the SF-S request message and that it is in bridge state. Node D also sends an SF-S request message on the long path.

When it receives the reverse request, node A executes a bridge-and-switch action; identical traffic is transmitted to node D on both working and protection fibers, and traffic from node D on the protection fiber is selected. Node A updates a request message to an SF-S bridge and switch. On receiving the message from node A on the short path, node D selects the protection fiber. Then it sends a reverse request on the short path and informs node A that it is in bridge-and-switch state.

Figure 5.31 illustrates the sequence of protection actions in the case of bidirectional signal failure. In this example, a cable cut occurs between

**Fig. 5.30** SF-S (span switch) sequence.
node A and node D. Node A and node D detect a signal failure condition on both their working and protection channels. Node A and node D send an SF-R request message to each other on the short and the long paths. Receiving these requests on the long path from both directions, node B and node C execute a bridge-and-switch action according to a predetermined traffic pattern map. When it receives the SF-R requests from node D on the long path, node A executes a bridge-and-switch action according to the traffic pattern map. Node A updates a request message to an SF-S bridge and switch. Node D does likewise.

5.5.2. NETWORK PROTECTION EQUIPMENT (NPE) AND TPC-5 CN

Figure 5.32 shows the network configuration of TPC-5 CN. The submarine cable accommodates two fiber pairs, and each fiber pair carries a 5 Gb/s signal. However, one fiber pair of the two fiber pairs in a cable is allocated for protection. The service traffic carried by a service fiber pair is protected
by NPE (network protection equipment), using transoceanic ring protocol through the protection fiber pair [21].

NPE has an SDH add/drop multiplexing function to aggregate STM-1 tributary signals to STM-16, together with a protection switching function. In addition, NME associated with NPE has the AU-4 path provision function. A block diagram of NPE is shown in Figure 5.33. NPE consists of high-speed (HS) interface, multiplexer/demultiplexer (MUX/DMUX), time slot assignment (TSA), and low-speed (LS) interface. An NPE overview is shown in Figure 5.34.

LS interfaces connect back-haul SDH terminal equipment with optical or electrical STM-1 signals and are protected by 1 + 1 redundancy. TSA performs add/drop pass and pass-through functions for STM-1 signals. The pass-through function bypasses a signal at the node. TSA also performs self-healing operations, which can automatically switch over traffic on the working time slots to the protection time slots. The MUX/DMUX section performs multiplexing and demultiplexing of STM-1 signals to/from STM-16 signals and suppresses jitters on STM-1/STM-16 signals. The HS interface section transmits and receives STM-16 signals, generates and terminates section overhead (SOH) of STM-16, and performs self-healing operations by means of detecting protection switch requests in SOH bytes triggered by AMS signals from an LTU.
5.5.3. NETWORK OPERATION AND MAINTENANCE

The network operation system is explained from the perspective of OAM&P activities, taking the TPC-5 CN system for an example. The cable station support staff are the first tier (Tier I, on-site workforce) of network management. These people are responsible for 24/7 network OAM&P and will investigate any network problems and take the appropriate action. Their responsibilities include traffic provision and network restoration against network failure [22].

All cable stations in the TPC-5 CN have NPEs providing automatic traffic restoration during network failures. As shown in Figure 5.35, in the two cable stations, San Luis Obispo and Miyazaki, the NME is collocated with NPEs and directly communicates with NPEs through a 10 Mb/s Ethernet. System supervisory equipment (SSE) is an element management system for TPC-5 CN’s network elements. NME can communicate with the remote station NPEs through an STM-16 overhead channel using a Q3 interface. All alarm events detected by NPEs are reported autonomously and collected by NMEs in real time.
Fig. 5.34  NPE overview.

Fig. 5.35  TPC-5 network operation systems.
Daily OAM&P activities must meet the cable owner’s requirements. The TPC-5 landing party of AT&T and KDDI (formerly KDD) are responsible for this requirement. They have established Tier I OAM&P activity programs to minimize impact on service traffic. Maintenance work is conducted during the time of least network usage and hazard notification is sent to the cable owners.

The second tier of network management is the Tier II (network operation center) network control function. In the TPC-5 CN cable network, this function is carried out by the primary network control center located in Denver, Colorado, with the secondary center in Tokyo, Japan. The network control centers can also coordinate network OAM&P activities outside of the TPC-5 CN when multicable system restoration or provision activities are required. They provide the point of contact with the cable owners on all network activity. As the network operation becomes steady state, they can take more a direct role of Tier I network management for the cable station equipment through the TMN link between the operation center and the cable station using NME and SSE, as shown in Figure 5.35.

5.5.4. OPTICAL NETWORK PROTECTION EQUIPMENT (ONPE) AND JIH CABLE

NPE protects the traffic paths for the time slot channels. The same protection mechanism can be used for the protection of wavelength channels in WDM systems. Optical NPE (ONPE) was developed for WDM submarine ring networks by adopting the transoceanic ring APS protocol for wavelength channels [23]. In order to furnish data format transparency, the signaling channels are separated from the traffic channels by being transported in-band or out-of-band. Signal performance is detected by the dedicated supervisory channel or the LTU of the SLTE.

ONPE was firstly deployed in JIH (Japan Information Highway) cable. The JIH submarine cable network configuration is shown in Figure 5.36 [24]. The JIH cable is KDDI’s private cable network, providing a large-capacity and high-reliability backbone network utilizing DWDM technologies, self-healing mechanisms, and a network management system.

The JIH is a 10,300 km trunk-and-branch network with 100 Gb/s bandwidth that was inaugurated on April 1, 1999. This network is capable of connecting most of the domestic local access networks with the international cable networks, such as TPC-5 CN, SEA-ME-WE3, APCN, and Japan–U.S. cables, through the 17 cable landing stations in the
Japanese archipelago. The network is divided into four subnetworks from the geological point of view by master cable stations (MCSes). The cable contains the three fiber pairs consisting of a local fiber pair (LFP), express fiber pair (EFP), and supplementary fiber pair (SFP). LFP is branched from the trunk cable by branching units and terminated by local cable stations (LCSes). The subnetworks constituted by LFP and EFP are protected by a collapsed ring network architecture, using NPE for fiber cut failure. In the event of a cable cut failure, traffic is protected by SFP using optical NPE (ONPE).

Figure 5.37 illustrates the JIH network management system, based on the TMN model. The MC is located in each cable station as an element management system in order to control and monitor JIH transmission equipment as network elements, where four out of 17 cable stations are called master cable stations (MCSes) and other cable stations are called local cable stations (LCSes). NMEs of both optical NPE and conventional NPE are located only in MCSes; however, MNE communication with remote NPEs in LCSes is carried between cable stations over an STM-16 overhead channel. In each cable station, standardized Q3 interfaces are adopted between
the MC and other network elements. All MCs are remotely controlled by one NOC located in the center of Tokyo.

JIH is also controlled and monitored by NWOS, KDDI’s network manager for transmission systems, by means of connecting the MC in each MCS using standardized Q3 interfaces. The NEOS in each LCS is also controlled and monitored by NWOS via MC in MCS. The JIH network management system and self-healing systems allow each cable station to have unmanned OAM&P operations, and both Tier I and Tier II operations are performed in a single, centralized NOC.

5.6. Future Submarine Networks

5.6.1. RECENT PROBLEMS IN TRADITIONAL SUBMARINE NETWORK CONFIGURATION

Traditional submarine networks have used SDH ring networks to provide TDM connectivity between cable stations with back-haul systems
to nearby major cities, as shown in Figure 5.38. Recently, this architecture has been stressed due to increased bandwidth requirements and the need for packet-switched data connectivity and seamless city-to-city connections. A new view of submarine cable networks is emerging, consisting of a mesh network that integrates submarine and terrestrial networks.

Figure 5.39 shows the current submarine network configuration. Traffic is aggregated at a city POP (point of presence) and delivered over SONET/SDH systems to a landing station, where it is further aggregated onto the submerged ring for transport to another landing station. At the destined landing station, the reciprocal process occurs: the traffic is disaggregated and sent on to the city POP. Although terrestrial and submarine networks, with their segregated OAM&P domains, have been partitioned so far, it has become clear that OAM&P needs are best served by end-to-end connectivity.

Fig. 5.38  Traditional global network.
The submarine network extends from POP to POP with a single OAM&P environment, and the distinction between submarine and terrestrial networks is blurred or eliminated. In general, the segmented environment of Figure 5.39 requires multiple OAM&P systems. As a result, the network management systems become unwieldy, with duplication of functionalities between the segments. In contrast, in a monolithic OAM&P environment, greater automation and economies of scale should inevitably result.

In the next generation of transoceanic submarine cables, the demand for larger capacity will be fueled in part by the popularity of the Internet and in part by businesses’ need to exchange data among distant locations. These needs have driven the development of DWDM technology to increase submarine transmission capacity dramatically. In such multiple-terabit submarine cable systems using DWDM technologies, hundreds of wavelengths at rates of 10 Gb/s or higher will be transmitted over a new cable accommodating more than eight fiber pairs. At the ring network node connecting multiple cables, thousands of wavelengths will be demultiplexed and terminated by SLTE at the shore-end, as shown in Figure 5.40. In addition, with traditional architecture, STM-64 systems are demultiplexed to tributaries at the cable station in order to transfer capacity to the terrestrial back-haul system placing SONET/SDH equipment. In multiple-terabit submarine cable systems, the amount of space to collocate...
the equipment, and also the power used by the terminal equipment, will increase significantly.

In terms of system cost, the terminal cost will become dominant in the total cost of a WDM submarine cable system. The unit price of wet plant may increase somewhat, but the increase of the cost is not proportional to the increase of the system capacity. Terminal equipment costs will increase in proportion to the number of wavelengths in the system. Accordingly, the total system cost will skyrocket.

The telecommunication industry shift from voice-optimized, circuit-switched services to data-optimized, packet-switched services is well under way. As a consequence, the value of SONET/SDH as an intermediate multiplexing layer is diminishing. Solutions are being developed that will carry IP traffic directly over DWDM; these solutions are being addressed by various standardization bodies to standardize the new network control optimized to such traffic transport. The concept of supporting data directly over optics has been fueled by the need to eliminate unnecessary network layers. This will lead to a vast reduction of equipment in the network. Therefore the cost, footprint, and complexity of the network are expected to drop.
5.6.2. SURVIVABILITY AND TOPOLOGY

Survivability is an essential ingredient in telecommunications networks. The network topology leads to different restoration schemes. In current submarine networks, the ring network architecture is widely used for network protection, as described in the previous sections. Ring networks can provide fast protection and use protection capacity on a preemptive basis. Mesh networks, however, offer a more flexible topology than ring networks and can adapt to changing traffic patterns more efficiently than ring networks, although in terms of the protection time, mesh networks are inferior to ring networks [25].

In mesh networks, there are generally multiple choices for the restoration path, whereas in ring networks, there is only one. Ring networks require allocation of the same amount of capacity for protection as for working. Namely, 1 : N protection is not available on separate fibers for N > 1. In other words, mesh networks use network protection and restoration capacity more efficiently than ring networks. For this reason, mesh networks are more forgiving under multiple failure scenarios and offer higher availability. In addition, for the multiple ring networks used for providing terrestrial network survivability, overbuild capacity will be required in the interconnecting links, as shown in Figure 5.41.

Fig. 5.41 Overbuild capacity in multiple ring networks.
Figure 5.42 shows the mesh network solution for submarine and terrestrial network connections. In this model, mesh networks share the protection capacity in the interconnecting link with the submarine and terrestrial working traffic. Furthermore, the mesh networks have the scalability that allows interconnection of the initial cable network and a cable segment installed later with arbitrary mesh topology.

5.6.3. OXC-BASED MESH NETWORKS AND THEIR BENEFITS TO SUBMARINE CABLE SYSTEMS

The key enabling technology for mesh networks is the optical cross-connect (OXC) furnishing an MPLS (multiprotocol label switching) network control plane. OXC will provide the capability to add/drop and cross-connect wavelength channels. OXC can switch hundreds of optical ports using optical switching fabric consisting of micromirror arrays fabricated by micro-electro mechanical system (MEMS) technology [26]. Label switching technology was originally developed as an IP routing scheme to forward packet traffic in a preassigned path without calculating the routing table at each router hop in layer 3. By applying the label swapping/forwarding paradigm at a label-switching router (LSR) to the optical port switching
at OXC, an MPLS control plane can be deployed in WDM optical mesh networking by being defined as MPLambdaS [27]. This scheme was also expanded to time slot by being defined as generalized MPLS (GMPLS) [28]. An MPLS-based mesh network paradigm can be used in a TDM system using time domain cross-connect.

GMPLS can provide protection and restoration, as well as routing functionality, in mesh networks, as shown in Figure 5.43. The ability to support wavelength-based networks is the key to keeping pace with unpredictable traffic demands by enabling bandwidth scalability and greater networking flexibility. OXC-based platforms can provide fast point-and-click, end-to-end provision of wavelength channels in a timely fashion.

For the management of large-scale OXC-based mesh networks, the ability to perform node and link autodiscovery is essential to facilitate the autonomous switching and routing functions. To enable such autodiscovery functions, the end-to-end path is established by RSVP or CR-LDP,
computing the optimal path using the constraint shortest path first (CSPF) algorithm based on the network topology and constraint information distributed by ISIS or OSPF flooding procedures. In terms of network scalability, the new paradigm can autodiscover new routes when new nodes are added. It also provides network protection and restoration capabilities by dynamic routing of a preestablished alternative path setup by MPLS.

The deployment of mesh networks will be useful in removing multiple transport domains and OAM&P infrastructures accommodating traffic in a common network platform. In particular, by applying an OXC-based mesh scheme to the submarine networks at the landing station, the aggregation of traffic to the wavelength removes the large number of tributary interfaces and SONET/SDH interconnection equipment associated with terrestrial back-haul networks by pushing the tributary interfaces to the network edges. The role of SONET/SDH network equipment will be taken over by OXC, whose footprint can be dramatically reduced thanks to wavelength granularity. The OXC-base cable station configuration is shown in Figure 5.44. The minimization of network equipment, together

**Fig. 5.44** OXC-based cable station configuration.
with the removal of SONET/SDH equipment interconnecting to terrestrial networks, will help to significantly diminish equipment costs.

5.6.4. FUTURE NETWORK SERVICES

The deployment of data networks to connect data centers across global networks is an important telecommunication service. Wavelength connectivity can simplify the network architecture. The data center is usually located in a metropolitan area and can be connected to other data centers through a direct wavelength connection. This is a major simplification in comparison to the present mode of operation, where the data traffic is transported with many hops through multiple IP routers and multiple facilities. Hence, direct optical end-to-end connection enables one hop routing and improves the performance of packet transport and the system economy. The advantage of optical layer networking will be enhanced as the service capacity increases.

References


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Part 3 | Applications
6.1. Introduction

The increase in data traffic resulting from the use of Internet- and Web-based services has meant that the features of access networks must become more flexible in order to provide various types of service and access while remaining cost effective. The wavelength we employ is important as regards the provision of various services and routing, as well as in terms of its role in increasing transmission capacity. Metropolitan area networks must also be flexible and have a large capacity to carry traffic from the access network. This chapter describes various wavelength-division multiplexing (WDM) technologies and typical WDM networks, including system configurations and field trials for access and metropolitan area networks. WDM schemes and related devices are also described, and methods of standardization and future trends discussed.

6.2. Current Features

Information networks are classified into user, access, metropolitan area, and core networks in terms of area and hierarchy. Figure 6.1 shows the information infrastructure and service applications. Various kinds of systems are employed in access networks; these include fiber to the home/building/curb
(FTTH/B/C), metallic line (x digital subscriber line [xDSL]), wireless, hybrid fiber coaxial (HFC), and satellite systems. Internet, CATV, leased lines, and telephony services are provided by these systems and by their specific networks. Infrastructure platforms for various services are constructed of these systems. The metropolitan area networks connect the access network traffic to the core and service networks.

Figure 6.2 shows the service trend. Broadband access services, including telephony, data transmission, and dial-up Internet services, are in use and growing rapidly. In particular, there has been a considerable increase in such services as music, video content distribution, and e-commerce. Such services require a large capacity and real-time transmission, and they are provided by mobile and dedicated lines, as well as by conventional telephony, ISDN, and CATV. This implies that the systems and networks must support various services and access styles to meet the needs of new ways of working, such as SOHO. For this reason, flexibility and cost effectiveness are key factors in the next generation of networks.

The increase in Internet and content distribution traffic has had an impact on networks and systems, as illustrated by the need for dedicated lines and a cost-effective Ethernet interface. The demand is increasing for
Various services and application styles

- Telephony, ISDN, TV/video
- satellite, computer, etc.
- Fixed telephone, PC, dial up

+ EC, music distribution (MP3), video distribution, auction, etc.
- Mobile, dedicated line (multi-QoS)

- Various services and application styles

- Flexibility
- Cost effective network

Fig. 6.2  Service trend.

Fig. 6.3  Media convergence.

cost-effective, high-speed IP access and support for access anywhere, at any time, and for any service.

Figure 6.3 shows the trend in content and systems. CATV and broadcasting services use different networks from those used for telephony and ISDN. Furthermore, all IP and leased lines use different service networks, although the telephony network and ISDN are now playing the most important roles. However, with the increase in content distribution and voice via IP as well as the Internet, most of the services that have thus far been transmitted over ATM, STM, and SCM will be provided by IP. IP will therefore become the main service infrastructure.
6.3. Current Status of Optical Technology

6.3.1. OPTICAL TECHNOLOGY FOR ACCESS AND METROPOLITAN AREA NETWORKS

One of the most important factors in relation to access and metropolitan area networks is cost effectiveness. This is because the cost per user and per service is important (as well as cost per channel) in these networks compared with core networks, where the only advantage is the bitrate, namely capacity.

Various transmission schemes are currently used for access networks, for example, digital transmission for SDH, analog transmission, and data transmission for Ethernet and fiber channels. Public telephony, LAN, WAN, and CATV transmission have also been introduced. This has led to the development of the following technologies for access and metropolitan area networks:

- The passive optical network (PON)
- Low-cost single-star transmission
- Various transmission schemes (e.g., Ethernet)
- Cost-effective optical module and device fabrication especially for WDM
- Low power consumption and high density assembly

6.3.2. WDM SCHEMES

Figure 6.4 summarizes the various WDM technologies for access and metropolitan area networks. The characteristics are compared in Figure 6.5. Dense WDM (DWDM), coarse WDM (CWDM), wide-passband WDM, and wide-WDM (1.3/1.5 μm WDM) schemes have been developed.

6.3.2.1. DWDM

In order to increase the transmission capacity and transmission distance available with optical amplifiers, a DWDM technique has been developed to provide as narrow as possible a wavelength/channel spacing in the appropriate wavelength region of optical amplifiers. This has led to the use of a wavelength spacing of 0.4–1.6 nm (200–50 GHz) in the 1500–1600 nm wavelength region (C and L bands). It is essential to realize precise wavelength control; that is, it is necessary to control the temperature and bias.
6. Optical Access/Metropolitan Area Network Using WDM

- DWDM (Dense-Wavelength-Division-Multiplexing)
  - Spacing: around 0.8 nm (200–50 GHz)
  - 1.5–1.6 μm: 1000 channels

- CWDM (Coarse-Wavelength-Division-Multiplexing)
  - Spacing: around 20, 40 nm etc.
  - 1.2–1.6 μm: around 10 channels

- Wide-passband WDM (Wide passband-Wavelength-Division-Multiplexing)
  - Spacing: around 20 nm
  - Passband: around 15 nm
  - 1.3–1.6 μm: around 18 channels

- Wide-passband WDM (1.3 /1.5 -WDM)
  - Spacing: around 250 nm
  - 1.3 μm,1.5 μm region: 2 channels

Fig. 6.4  WDM schemes.

<table>
<thead>
<tr>
<th></th>
<th>Light source</th>
<th>Filter</th>
<th>Cost</th>
</tr>
</thead>
<tbody>
<tr>
<td>DWDM</td>
<td>wavelength control, external modulator</td>
<td>Spacing: around 0.8 nm wavelength control</td>
<td>high</td>
</tr>
<tr>
<td>CWDM</td>
<td>FP-LD, DFB-LD temperature control</td>
<td>Spacing: around 20, 40 nm etc.</td>
<td>medium</td>
</tr>
<tr>
<td>Wide-passband WDM</td>
<td>DFB-LD without control</td>
<td>Spacing: around 20 nm passband: around 15 nm</td>
<td>medium</td>
</tr>
<tr>
<td>Wide-WDM (1.3/1.5 μm)</td>
<td>FP-LD</td>
<td>1.3 1.5 μm</td>
<td>low</td>
</tr>
</tbody>
</table>

Fig. 6.5  Comparison of various WDM schemes.
current of laser diodes (LDs) and filters. LD oscillating wavelength monitoring techniques and oscillating wavelength rocking techniques have been introduced for accurate wavelength setting. Distributed feedback laser diodes (DFB-LDs) and electro-absorption (EA) modulators are now in practical use as DWDM sources, where these devices are selected for each wavelength. Dielectric thin-film filters, arrayed waveguide gratings (AWGs), and fiber gratings are also used for multiplexing and demultiplexing. In addition, temperature controls are used to stabilize the wavelength characteristics of these optical filters. The additional control circuits needed for setting the wavelength accurately increase the cost of systems that use DWDM, although more than 100 wavelengths can be multiplexed in one fiber. DWDM is mainly employed in trunk transmissions for terrestrial and submarine systems. The nonlinear effect known as four-wave mixing (FWM) is generated with long zero-dispersion wavelength transmissions with an equal wavelength spacing.

However, there is a possibility of realizing cost-effective DWDM because of the large-scale production of DWDM optical devices, such as DFB-LDs and filters. The ability to control wavelength only by controlling the temperature, without the need for wavelength monitors, is useful and reduces cost, compared with conventional DWDM in core networks. The wavelength for cost-effective DWDM has around a 3 nm spacing.

### 6.3.2.2. CWDM

One of the cost-effective approaches is CWDM [1, 74]. Various wavelength allocations have been proposed for CWDM. A wavelength spacing of 20–40 nm is typically used. The approach employs directly modulated DFB-LDs and FP-LDs, dielectric thin-film filters, fiber couplers, and polymer waveguides. Cost-effective devices are important for CWDM. The wavelength controls are removed, but some coolers (fans) are used. CWDM is used in LANs and WANs. In some cases, CWDM includes wide-passband WDM and wide-WDM (1.3/1.5 µm WDM) [29], described in the sections that follow. In particular, CWDM with wavelength spacing of 20 nm is almost same as wide-passband (WWDM).

### 6.3.2.3. Wide-passband WDM

Another cost-effective solution is wide-passband WDM. In particular, wide-passband WDM is the same as CWDM standardized by ITU-T. Wide-passband WDM widens the wavelength passband to around 15 nm, with
the CWDM wavelength spacing of about 20 nm. Widening the passband makes it possible to use LDs and filters without wavelength controls, such as temperature controls. DFB-LDs without temperature control and dielectric thin-film filters are practically useful. The cost effectiveness and high power budget are the same as those of DWDM. Wide-passband WDM has been proposed as a technology for realizing 10 gigabit Ethernet (GE) and access networks.

Figure 6.6 shows the wide-passband WDM concept for access networks. A wavelength spacing of 20 nm and an operating temperature range of 100°C are assumed. DFB-LDs, whose wavelengths match the ITU-T standard, are useful in this context. This is because the wavelength variation of a DFB-LD (0.1 nm per degree) is only 10 nm when the temperature changes in 100°C steps. In wide-passband WDM, the DFB-LD selection is convenient and eliminates the need for the additional control circuit for wavelength setting. This is expected to provide both simplicity and cost effectiveness. The key wide-passband WDM technologies are wide passband filters and inexpensive, uncooled DFB-LD modules. High-performance wide-passband filters with a loss of 1 dB or less and a crosstalk of 5 dB/nm or more are achieved by using dielectric thin film [2].

6.3.2.4. Wide-WDM (1.3/1.5 µm WDM)

The wavelength spacing for Wide-WDM (1.3/1.5 µm WDM) is over 250 nm. This WDM multiplexes the 1.3 and 1.5 µm wavelength regions. Fabry–Perot laser diodes (FP-LDs), fiber coupler filters, and dielectric
filters are useful in this regard. This is the most cost effective of these WDM schemes. For example, the fiber to the home (FTTH) system integrates the STM-PDS (bidirectional by TCM/TDMA) for 1.3 \( \mu \text{m} \) and the SCM-PDS (analog video distribution) for 1.5 \( \mu \text{m} \) [3].

Figure 6.7 shows the wavelength setting accuracy and channel number (wavelength number). The wavelengths are assumed to be in the 1.3–1.6 \( \mu \text{m} \) region. A maximum channel number of about 16 can be achieved with wide-passband WDM and CWDM. In contrast, more than 100 channels are useful for DWDM. The cost of wide pass-band WDM and CWDM can be reduced depending on the wavelength setting accuracy.

6.3.3. OPTICAL COMPONENTS

6.3.3.1. WDM Light Sources

Figure 6.8 shows the light sources for WDM transmissions. The spectral characteristics of a light source are the most important factor in system construction. Light sources, such as LEDs, FP-LDs, and DFB-LDs, are used in practical WDM systems. Tunable LDs and multiwavelength light sources are expected to be employed for various WDM applications.

**DFB-LDs**

LDs with stable and accurate oscillating wavelengths and narrow spectral widths are needed for WDM transmissions. A reduction in the WDM
### LED
- Multi-longitudinal mode LD
  - FP-LD
- Single-longitudinal mode LDs
  - DFB-LD
  - Hybrid LD (with fiber grating, on PLC)

### Tunable light sources
- SSG-LD
- GCSR-laser

### Multi-wavelength light sources
- LED
- ASE
- Super continuum (SC) light source
- Multifrequency laser (MFL)
- Mode locked LD
- Chirped pulse LD

**Fig. 6.8** Light sources for WDM transmission.

Wavelength spacing means that more precise wavelength setting and controls are required. LD fabrication techniques have been developed to meet the requirements for LDs for WDM applications, namely metalorganic vapor phase epitaxy (MOVPE) with a large wafer, electron beam (EB) Bragg grating fabrication, and selective-growth MOVPE. These techniques improve the oscillating wavelength uniformity of the DFB-LD, the LD chip yield, and mass production. Moreover, LDs of different desired wavelengths can be fabricated in the same wafer. A hybrid light source consisting of an LD and a fiber grating, and an LD and waveguide grating on a PLC have been investigated [77]. Because the oscillation wavelength is determined by the grating, the desired wavelength is easily obtained.

**Tunable LDs**

Wavelength-tunable LDs have been investigated to obtain the desired oscillating wavelength. The LDs usually have several sections for such functions as oscillation and control, and have several electrodes. Control processors and circuits are needed to tune the LD wavelength to the desired value. The tuning (wavelength switching) time, useful wavelength regions, and reliability are important in terms of WDM light sources. The tunable LD
is attractive for time domain wavelength packet routing and redundant transmission line (standby) sources, as well as for WDM transmissions [4, 5, 78].

**Multiwavelength Light Sources**

Multiwavelength light sources simultaneously oscillating at different optical wavelengths have been investigated for WDM transmission. These light sources can avoid the need for a light source oscillating at a precisely specified WDM wavelength. Spectrum-slicing techniques can be achieved by using these multiwavelength light sources in conjunction with WDM filters and WDM routers. The following multiwavelength light sources have been reported: LED and amplified spontaneous emission (ASE) sources [6–11], a super continuum (SC) light source [12, 13], a frequency comb generator using a mode-locked LD and a modulator [14, 15], a multifrequency laser (MFL) based on the integration of a waveguide grating router (WGR) with an optical amplifier [16].

6.3.3.2. **Detector**

The PD and APD used for single-wavelength transmission are used also for WDM transmission. The PD and APD have a sensitivity of up to 1.6 µm. The desired wavelength is selected by the WDM filters used in the optical demultiplexing. High sensitivity over a wide wavelength region and low power consumption are important. The superlattice APD is an attractive candidate, because of its wide band and high gain with a low operating voltage.

6.3.3.3. **Optical Filters for Optical MUX/DMUX**

Optical filters are required that have low loss and high channel crosstalk. A narrow wavelength spacing for DWDM and a wide, flat passband for wide-passband WDM are also required. Dielectric thin-film filters are still employed for various WDM schemes. Planar lightwave circuits (PLCs) and AWGs are attractive as regards increasing the wavelength number of the filters, because their use allows an optical MUX/DMUX incorporating each channel filter to be integrated in one chip. Fiber couplers and fiber gratings are also used, and their performance has improved. Polymer-based filters have also been developed with a view to cost reduction. Figure 6.9 summarizes these optical filters [17].
6.3.3.4. Optical Fibers

Because fiber must exhibit low loss and low dispersion for high bitrate transmissions, nonlinear effects, especially four-wave mixing (FWM), must be reduced for DWDM transmissions. This is more strictly required for narrow wavelength spacing and long-haul transmissions. An unequal wavelength spacing allocation is used and the input power is restricted to avoid FWM in the fiber. Standard SMF is mainly used in access and metropolitan area networks. However, various optical fibers have been developed for WDM transmissions. They are nonzero dispersion shifted fibers and large core area fibers, which are typically used in core and submarine WDM transmissions. These fibers can avoid the generation of FWM in the signal transmission wavelength region. To expand the wavelength region for WDM transmission, a low-loss fiber for the 1.3–1.6 \( \mu \text{m} \) region has also been developed, which is expected to be used in access and metropolitan area networks. Table 6.1 shows the various kinds of fibers used for WDM transmission.

6.3.3.5. Optical Fiber Amplifiers

Distribution systems use optical amplifiers. Erbium-doped silica fibers and 1.48 and 0.98 \( \mu \text{m} \) pump-LDs are practically used for the C and L bands. High gain, high saturation power, and a wide flat gain region are required. Fiber amplifiers have been developed for the 1.3 \( \mu \text{m} \) region and the S band.
Table 6.1 Various Fibers for WDM Transmission.

<table>
<thead>
<tr>
<th>Type</th>
<th>Dispersion $D$ (ps/km/nm)</th>
<th>Dispersion slope (ps/km/nm$^2$)</th>
<th>Mode field ($\mu$m) at 1550 nm</th>
<th>Product</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>$2.6 \sim 6.0$</td>
<td>$&lt;0.05$</td>
<td>$8.4 \pm 0.6$</td>
<td>TrueWave RS</td>
</tr>
<tr>
<td></td>
<td>$1530 \sim 1565$ nm</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>2</td>
<td>$-1.4 \sim -4.6$</td>
<td>$&lt;0.112$</td>
<td>$9.5 \pm 0.6$</td>
<td>TrueWave XL</td>
</tr>
<tr>
<td></td>
<td>$1550$ nm</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>3</td>
<td>$-1.4 \sim -4.8$</td>
<td>$&lt;0.05$</td>
<td>$8.4 \pm 0.6$</td>
<td>TrueWave SRS</td>
</tr>
<tr>
<td></td>
<td>$1550$ nm</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>4</td>
<td>$-10.0 \sim -1.0$</td>
<td>$-$</td>
<td>$7.6 \sim 8.6$</td>
<td>MetroCor</td>
</tr>
<tr>
<td></td>
<td>$1530 \sim 1605$ nm</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>5</td>
<td>$2.0 \sim 6.0$</td>
<td>$&lt;0.12$</td>
<td>$9.2 \sim 10$</td>
<td>LEAF</td>
</tr>
<tr>
<td></td>
<td>$1530 \sim 1565$ nm</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>6</td>
<td>$5.5 \sim 10.0$</td>
<td>$&lt;0.058$</td>
<td>$9.2 \pm 0.5$</td>
<td>TeraLight</td>
</tr>
<tr>
<td></td>
<td>$1530 \sim 1565$ nm</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Figure 6.10 Optical fiber amplifiers versus amplification wavelength.

Figure 6.10 shows the various optical fiber amplifiers. The wavelength bands are defined in ITU-T as follows:

- **O-band**: 1260–1360 nm
- **E-band**: 1360–1460 nm
- **S-band**: 1460–1530 nm
- **C-band**: 1530–1565 nm
- **L-band**: 1565–1625 nm
- **U-band**: 1625–1675 nm
6.3.3.6. Optical Modules

Optical modules, particularly the LD module and the filter module, are some of the most important components in terms of access network cost reduction. This is because the optical coupling and assembly of an LD and filter with a fiber require precise alignment while monitoring the optical power. Furthermore, miniaturized modules for each wavelength are attractive for WDM transmission equipment applications in terms of improving integration efficiency.

Techniques for improving cost effectiveness have been proposed for FTTH with regard to assembly [18, 19]. These techniques involve the use of passive alignment, a spot-size converted LD (SSC-LD) or beam-expanded LD, a plastic molded module, and a PLC platform for the hybrid integration of an LD, a PD, and a WDM filter (wide-WDM [1.3/1.5 µm WDM]). These optical modules were developed and used in some ONTs (optical network termination) for FTTH. This is shown in Figure 6.11. The modules can multiplex/demultiplex 1.3 µm bidirectional signals by means of time-compression multiplexing (TCM). The design concept is as follows:

1. Reduce the number of components in the module. This module consists of a PLC platform on which an SSC-LD is mounted, a waveguide PD (WGPD) and a monitor WGPD, a 1.3/1.5 µm WDM filter, a preamplifier, fibers, and a ceramic substrate.
2. Utilize passive alignment in assembling the SSC-LD and the WGPDs on the PLC. The SSC-LD and WGPDs have spot sizes as large as those of the PLC and fiber, resulting in a coupling tolerance that is sufficiently large for passive alignment.
3. Mount the bare preamplifier chip on a ceramic substrate to reduce the parasitic capacitance. The coupling loss is lower than 2 dB, and the 1 dB down-alignment tolerance is wider than ±2 µm, which means a loss of less than 5 dB is easily obtained for the SSC-LD.

Low-parasitic packaging for the laser diodes and PD mounted on the PLC platform has been developed, and its reliability confirmed under various environmental and endurance tests [19]. The median life of the modules was estimated to be more than $10^5$ h in an atmosphere of 45°C and 85% RH. No failures have been observed in a temperature-cycling test in the −40 to 85°C range for over 2000 cycles. These plastic modules containing laser diodes and photodiodes are attractive for low-cost applications. The optical module technologies are shown in Figure 6.12.
6.3.4. FEATURES OF WDM TECHNOLOGY

Figure 6.13 shows an example of WDM features DWDM and wide-WDM (1.3/1.5 μm WDM). The wavelength control requires temperature control, and wavelength monitoring and feedback circuits for each LD and filter, resulting in additional circuits and power consumption and increased cost.
Fig. 6.12  Technical trends in optical modules.

<table>
<thead>
<tr>
<th>Relative cost</th>
<th>Hybrid integration type</th>
<th>Monolithic</th>
</tr>
</thead>
<tbody>
<tr>
<td>Discrete type</td>
<td>Assembly time</td>
<td>&lt;1/20</td>
</tr>
<tr>
<td>Number of Components</td>
<td>1</td>
<td>&lt;1/4</td>
</tr>
</tbody>
</table>

Fig. 6.13  WDM features.

<table>
<thead>
<tr>
<th>Wavelength control</th>
<th>DWDM</th>
<th>Wide-WDM (1.3/1.5 µm) WDM</th>
</tr>
</thead>
<tbody>
<tr>
<td>Temperature control</td>
<td>(LD, filter)</td>
<td>Without control (uncooled)</td>
</tr>
<tr>
<td>Electric power consumption for WDM</td>
<td>2W~</td>
<td>~0 W</td>
</tr>
<tr>
<td>Wavelength region</td>
<td>1.53 ~ 1.58 µm</td>
<td>1.26 ~ 1.35 µm</td>
</tr>
<tr>
<td>1.53 ~ 1.58 µm</td>
<td>1.53 ~ 1.56 µm</td>
<td></td>
</tr>
<tr>
<td>Center wavelength interval</td>
<td>200 GHz (0.8 nm)</td>
<td>200 GHz (1.6 nm)</td>
</tr>
<tr>
<td>100 GHz (0.8 nm)</td>
<td>200 nm~</td>
<td></td>
</tr>
</tbody>
</table>

**Requirements for system cost reduction**

- System design with no need for precise wavelength control
- New device technology
Furthermore, the LD and filter for WDM must be fabricated for each specified wavelength. This means that optical devices for WDM are small in quantity and of various kinds in terms of wavelength. One possibility is to develop a system configuration that relaxes the need for precise wavelength tuning. Another is to create new device technologies, for example, a more universal wavelength tunable device, and process technologies for simultaneous multiwavelength device fabrication.

6.4. WDM System for Access and Metropolitan Area Networks

6.4.1. WAVELENGTH REGION FOR WDM TRANSMISSIONS

The concept of WDM was proposed in the early stages of optical communications research before 1980. Because 0.85 µm was selected as the wavelength for optical transmission, WDM began in this wavelength region. The trend in optical transmission, especially in trunk transmission, is to use the 1.3 and 1.5 µm regions, and so WDM also uses these regions.

The typical WDM wavelength regions are summarized in Figure 6.14. WDM in the 1.2 and 1.3 µm regions is used in 6 Mb/s multimode fiber systems [20]. With regard to trunk transmissions, considerable effort has been made to increase the wavelength density, namely to increase the number of channels. WDM transmission is effective in increasing capacity when combined with optical amplifiers, which are used in the C and L bands. DWDM and super DWDM were developed for use in these regions. S-band transmission is also being developed, and cost-effective approaches are being proposed. Various CWDM systems are used in the 0.85–1.5 µm region. They employ single-mode fiber and multimode fiber. These systems are applied to LANs and WANs. Wide-passband WDM technology has been proposed with a view to improving the wavelength density and transmission distance of CWDM. With CWDM and wide-passband WDM, the wavelength region is expected to be in the 1.3–1.6 µm region, that is, in the O, E, S, C, and L bands. The goals for WDM are

- To increase the wavelength density (increase the number of channels)
- To expand the wavelength region
6. Optical Access/Metropolitan Area Network Using WDM

6.4.2. ARCHITECTURE

6.4.2.1. Point to Point

Point-to-point systems are fundamental transmission systems in the field of optical transmission. WDM is used mainly to increase the total fiber capacity. Transponders are employed that convert the input signals into desired wavelengths. These consist of an LD with a specified oscillating wavelength, a driver-IC, a PD or an APD, a preamplifier, a receiver circuit for WDM transmission, and optical or electrical interfaces for local (intraoffice) transmission.

Figure 6.15 shows typical WDM systems for point-to-point transmission. These systems have two clear uses: one is long-haul and large-capacity transmission; the other is LAN and WAN applications. The former uses DWDM and super DWDM in the 1.5–1.6 μm region (C and L bands). These systems are cost effective in terms of bitrate and distance, when used in combination with optical amplifiers. Therefore, high wavelength density is important. The latter includes CWDM, wide-passband WDM, and wide-WDM (1.3/1.5 μm WDM), which can provide cost-effective systems with low-cost devices. The fiber specifications have few limitations in that both

Fig. 6.14 Wavelength regions for WDM.
SMF and DSF can be used. The metropolitan area and access networks have the following features:

- Various user interfaces are provided, such as Ethernet (Fast Ether, Gigabit Ether) and fiber channels, as well as SDH.
- CWDM and wide-passband WDM systems are more attractive for LAN-to-LAN connections. The wavelength spacing is more than 20 nm.
- A WDM media converter with only Ethernet IF, such as wide-WDM (1.3/1.5 µm WDM), has appeared that enables the fiber transmission distance of LANs and WANs to be extended.

### 6.4.2.2. Point to Multipoint

Point-to-multipoint systems have star configurations, which are attractive in access networks. Passive optical networks (PONs) are typical point-to-multipoint systems. These systems consist of optical couplers or optical power dividers to deliver signals to individual points. TCM/TDMA and broadcasting schemes are used in one fiber in PONs.

Various PON systems have been proposed, namely STM-PON, SCM-PON, B-PON (broadband PON), E-PON (Ethernet PON), GE-PON, G-PON, Super-PON, and WDM-PON. Table 6.2 summarizes these systems. B-PON is making it possible to increase the bitrate for broadband services by using ATM, E-PON, and GE-PON are used for data communication to
Table 6.2  PON Systems.

<table>
<thead>
<tr>
<th>Type</th>
<th>Features</th>
<th>Standardization</th>
</tr>
</thead>
<tbody>
<tr>
<td>STM-PON (PDS) and SCM-PON (PDS)</td>
<td>STM, 50 Mb/s, Bidirectional by TCMA (1.3 µm) and video distribution (1.55 µm)</td>
<td>ITU-T G983/Q.834 series</td>
</tr>
<tr>
<td>B-PON*</td>
<td>ATM, 156M, 622M, 1.2G (down) Bidirectional by WDM (1.3/1.49 µm)</td>
<td></td>
</tr>
<tr>
<td>E-PON</td>
<td>Ethernet frame, 100–600 M Bidirectional by WDM (1.3/1.49 µm)</td>
<td></td>
</tr>
<tr>
<td>GE-PON*</td>
<td>Ethernet frame, 1.25 G Bidirectional by WDM (1.3/1.49 µm)</td>
<td>IEEE 802.3EFM (1000Base-PX)</td>
</tr>
<tr>
<td>G-PON*</td>
<td>Generic frame, 1.2 G, 2.4 G, 156 M (up), 622 M (up) Bidirectional by WDM (1.3/1.49 µm)</td>
<td>ITU-T G.984 series</td>
</tr>
<tr>
<td>Super-PON</td>
<td>Feeder line and drop section 2.4 Gb/s (down), 311 Mb/s (up)</td>
<td></td>
</tr>
<tr>
<td>WDM-PON</td>
<td>Assign wavelength to user, service, etc.</td>
<td></td>
</tr>
</tbody>
</table>

*: Video distribution services can be overlayed at 1.55 µm wavelength.
STM-PON (PDS): synchronous transfer mode passive optical network (passive double star)
SCM-PON (PDS): sub-carrier multiplex passive optical network (passive double star)
B-PON: broadband passive optical network
E-PON: ethernet passive optical network
GE-PON: gigabit ethernet passive optical network
G-PON: gigabit passive optical network
Super-PON: super passive optical network
WDM-PON: wavelength division multiplexing passive optical network

transmit Ethernet signals directly. The user network interfaces are 10Base, 100Base, and 1000Base Ethernet signals. G-PON supports the full services with gigabit rate, which uses generic frame. The video distribution can be overlayed at 1.55 µm in the B-PON and G-PON. Super-PON consists of feeder line (90 km) and drop line (10 km), covering a large total area of around 15,000 living units. WDM-PON is expected to be used to upgrade these PONs and wavelengths assigned for services and ONUs.

6.4.2.3.  Ring and Mesh

Optical ring-and-mesh networks are attractive as metropolitan area networks. In some cases, the access systems are connected to the nodes of metropolitan area network ring systems. In other cases, however, several users and offices are connected as nodes in a ring configuration. This is the application to closed area networks. The wavelengths are assigned to each node and dropped, or other wavelengths are added to the ring. Optical or electric add/drop MUXes (ADMs) are used in this configuration. In some
cases, several nodes are directly connected in ring configurations. This style of connection forms a mesh configuration, and a cross-connect is necessary in the mesh. Furthermore, WDM cross-connects will be introduced in the mesh.

Traffic protection is important in rings. Protected optical links between any two ring nodes can be realized by establishing a working path and a protection path. There are bidirectional and unidirectional rings. In unidirectional rings, both fibers should be installed in separate ducts or cable [21].

6.4.3.  WDM SYSTEMS

6.4.3.1. Access Networks

FTTH/FTTB/FTTC

FTTH is an abbreviation of fiber to the home, which is a system in which optical fibers from a central office (building) are directly connected to individual houses. FTTB and FTTC are abbreviations of fiber to the building and fiber to the curb, respectively, where data from a building or a curb installation are usually transmitted to a house by metal line.

CATV Video Transmission System (STM-PON, SCM-PON)

A typical FTTH system is the CATV video transmission system developed by NTT [3]. This system was introduced in Totsuka, Yokohama, Japan (Kanagawa prefecture), in 1997, and was the world’s first full-scale FTTH system. Passive double-star (PDS) technology is used to reduce the cost of optical access networks. This made it possible to introduce both an STM-PDS system to provide communication services and an SCM-PDS system to provide CATV video transmission service through one optical fiber.

Wavelengths of 1.3 and 1.5 µm are employed for the communication service (ISDN) of the STM-PDS system and the video transmission service (distribution) of the SCM-PDS system. In this way, the system integrates the two PDS systems by using WDM technology. Figure 6.16 shows the configuration of this CATV video transmission system. Here, the PDS system is a typical access network system in which a central office terminal, a narrow-band optical line termination (N-OLT), and an optical fiber can be connected to a number of narrow-band optical network units (N-ONU)¹

¹The optical network unit (ONU) in this section is the same as the optical network termination (ONT) used in FTTH standardizations.
Fig. 6.16 CATV video transmissions system.
### Table 6.3 Main Features of the CATV Transmission System.

<table>
<thead>
<tr>
<th>Item</th>
<th>Parameters</th>
</tr>
</thead>
<tbody>
<tr>
<td>Video signal format</td>
<td>NTSC</td>
</tr>
<tr>
<td>Number of channels (example)</td>
<td>40</td>
</tr>
<tr>
<td>Modulation type of video signal</td>
<td>VSB-AM</td>
</tr>
<tr>
<td></td>
<td>64-QAM (4 ch/crrier)</td>
</tr>
<tr>
<td>Frequency range of video signal</td>
<td>70–770 MHz</td>
</tr>
<tr>
<td>Wavelength of video signal</td>
<td>1550 ~ 1560 nm</td>
</tr>
<tr>
<td>Wavelength of communication signal</td>
<td>1300 nm band</td>
</tr>
<tr>
<td>Line bitrate of communication</td>
<td>52 Mb/s</td>
</tr>
<tr>
<td>signal</td>
<td></td>
</tr>
<tr>
<td>Communication signal format</td>
<td>Binary baseband</td>
</tr>
<tr>
<td>Modulation type of optical signal</td>
<td>Intensity modulation</td>
</tr>
<tr>
<td>Transmission length</td>
<td>From OLT to ONU: 7 km</td>
</tr>
</tbody>
</table>

via an optical splitter. This optical splitter is a passive device and splits an optical signal into many signals. The communication service uses the N-OLT, the N-ONU, and 1.3 μm optical signals. The video transmission service uses terminals called video-optical line terminations (V-OLT), video optical network units (V-ONU), and 1.5 μm optical signals.

A 1.5 Mb/s user interface is provided for each N-ONU. The line bitrate is 52 Mb/s and TCM/TDMA is used; namely, bidirectional transmission at 1.3 μm is realized. Analog video signals consisting of 40 AM carriers (40 channels) and 64 QAM digital video signals consisting of 30 carriers (120 channels) are distributed by the head end to each V-ONU through fiber amplifiers. The wavelength range of 1550–1560 nm appropriate for fiber amplifiers is used to distribute the SCM-PDS video signals. Considerable effort has been made to reduce the cost of ONUs integrating the WDM devices. The main features of the CATV video transmission system are shown in Table 6.3.

**B-PON System (G.983.1)**

The ATM with the following requirements has been adopted in order to realize a cost-effective, high-speed service system [22]:

- An access system platform is constructed that allows one system to offer multiple services and thus reduce the cost of facilities.
and operations. The ATM subscriber system has been developed as an access platform to support both existing and new services. In contrast, the conventional approach is to use different hardware to support each service.

- Hardware must be mass-produced. When all carriers can use the same hardware, fabrication runs can be increased and unit cost reduced. The ATM subscriber system is produced based on common technical specifications with a view to globalization.
- State-of-the-art CMOS LSIs and optical technologies have been introduced that enable us to realize compact and low-cost hardware. This results in reduced power consumption and low running cost, which also benefit the environment.

A typical system configuration is shown in Figure 6.17(a). The ATM subscriber system consists of an ATM optical line terminal (ATM-OLT), an ATM optical network terminal (ATM-ONT), and a network element operation support system (NE-OSS). ATM-OLT has ATM-PON interfaces, ATM traffic control, and SNI functions, as well as such transport interfaces as SDH and PDH and a single-star access line interface. ATM-ONT terminates the ATM-PON interface and provides customers with various ATM user network interfaces. ATM-OLT and ATM-ONT can be separated by up to 20 km, which satisfies the requirements of full-service access network (FSAN) carriers. Two types of access lines are defined: two-fiber and one-fiber types. The former type uses the 1.3 µm wavelength for both upstream and downstream transmission. The latter type employs WDM technologies and uses 1.3 µm for upstream transmission and 1.5 µm for downstream transmission. The one-fiber type is used to reduce access line cost. The maximum splitter number is 32. Fifty-three byte ATM cells are used for downstream transmission, and 56 byte cells are used for upstream transmission. The additional three bytes are used to set the guard time, preamble, and delimiter. The frame length is 152.67 µsec. For the 155.52 Mb/s ATM-PON interface, the information downstream transmission capacity is 149.97 Mb/s.

The ATM-PON needs a mechanism to prevent cells sent from ATM-ONTs to an ATM-OLT from colliding with each other on the shared access line, because up to 32 ATM-ONTs are connected to the same ATM-OLT. This is realized by providing the ATM-OLT with a ranging function. The function measures the distance between the ATM-OLT and all connected ATM-ONTs and instructs each ATM-OLT to add an appropriate delay such that all ATM-ONTs are the same virtual distance from the ATM-OLT. Then,
each ATM-ONT can transmit only at the cells assigned by the ATM-OLT, thus preventing cell collision. Because the downstream signal is broadcast from the ATM-OLT to all connected ATM-ONTs, an appropriate ATM-ONT can retrieve the information. This is realized with a data churn function. A password is defined in each ATM-ONT. The ATM-OLT checks the ATM-ONT password in the initial stage.

The first FTTH trials based on FSAN/G.983 ATM-PON (B-PON) were carried out by BellSouth from 1999 to 2000 [23]. A subdivision of about 400 homes in North Atlanta, Georgia, participated in these trials. Three
access line interfaces were used: a 155 Mb/s ATM-PON for PC, a video PON for TV (CATV), and existing copper pairs for telephones. WDM wavelengths of 1.3 and 1.5 µm were used for upstream and downstream transmissions, respectively. And the TV (CATV) services are provided at 1.55 µm by another parallel fiber. From 27 to 32 customers were supported by one PON system. Figure 6.17(b) shows the system configuration.

**Video Overlaid B-PON (G.983.3)**

The joint trial of data stream and video services multiplexing in B-PON system was conducted by NTT in 2002 in the Tokyo metropolitan area in Japan. The IP upstream and downstream, up to 100 ME for user, are assigned to 1.3 µm and 1.49 µm, respectively. Further, video signal of NTSC-TV-500chs (HDTV 100chs) is assigned to 1.55 µm. The three waves were multiplexed in one fiber. Figure 6.18 shows the B-PON trial configuration [79].

**Super-PON**

Super-PON architecture supports long-range transmission, a high splitting factor, and a large bandwidth capacity. These features require a high optical power budget. A straightforward way to increase the power budget is to
introduce optical amplifiers in the PON architecture. The advantage of using optical amplifiers is their transparency as regards format, bitrate, and wavelength. In terms of increasing the capacity, raising the bitrate is selected before wavelength-based multiplexing, because of the superior cost effectiveness of the former.

The super-PON system configuration is shown in Figure 6.19 [24]. The realized system parameters are a total splitting factor of 2048 and a span of 100 km. The span consists of a maximum feeder length of 90 km and a drop section of 10 km. The transport system supported on the super-PON is based on asynchronous transfer mode (ATM) cells. A downstream bitrate of 2.5 Gb/s is distributed to the ONUs using time-division multiplexing (TDM). A time-division multiple access (TDMA) protocol is used to share the 311 Mb/s upstream bitrate. In order to assure efficient upstream transmission with minimum overhead in the upstream transmission direction, all the ONUs are synchronized in time. The overall time synchronization of the ONUs, called ranging, is realized during system initialization, and its stability is constantly verified during operation.

The WDM upgrade system of the super-PON is composed of four major building blocks:

- An access node with OLTs connected to narrowband/broadband switches in a core network

![Super-PON system diagram](image)

Fig. 6.19 Super-PON system.
An all-optical node connected to an all-optical network
- Optical repeater units (ORUs), including optical amplifiers
- ONUs

The access network interfaces with the all-optical network at an all-optical node. Each OLT emits at a specific wavelength and addresses a separate group of ONUs. These super-PON wavelengths are combined at the all-optical node with the channels from the all-optical core network and travel along the upgraded super-PON in order to address the different ONUs.

A super-PON demonstrator is working and was presented for the first time in 1999 [24]. Several ONUs were connected to an OLT via a cascade of amplified splitter ORUs. PC video applications were demonstrated and exchanged between two user PCs, both connected to an ONU. The OLT and ONU ASICs are the key elements of the system because they support the transport system. They are implemented through the use of 0.35 µm CMOS technology. The OLT offers a number of STM1 interfaces on the network side, and the ONU offers a link to two ATM forum interfaces on the user side.

**Ethernet Direct Transmission**

The direct transmission of Ethernet signals is attractive as regards Internet traffic, and media converters in LANs are candidates for providing this function. These converters can connect PCs and switches on a user’s premises to LAN switches and Internet-based services at a telephone center by using optical fiber with a simple and low-cost network. This is point-to-point transmission. WDM technology is used for upstream and downstream transmissions, with assigned wavelengths [25]. Here, two fibers are also used: one for upstream transmission and the other for downstream transmission. The LAN and WAN configurations can be employed in access networks.

**6.4.3.2. Metropolitan Area Networks**

**OADM Ring System**

In metropolitan area networks, most traffic is concentrated between a center node and remote nodes, and a logical star connection can adequately handle the traffic. A ring connection, such as OADM, is suitable for this type of traffic. Unidirectional OADM ring systems have been demonstrated [26].
The 10 Gb/s × 32ch prototype has a 100 GHz channel spacing in the L-band for DSF. The node and regeneration spans are 240 km, and there are three node spans. Figure 6.20 is a diagram of the OADM ring system and reconfigurable OADM node. Network elements (NEs, i.e., OADM node and repeater) connected by two fibers were used to construct two unidirectional rings: one clockwise (CW) and one counterclockwise (CCW). A data signal was transmitted through both rings simultaneously and selected at the receiver node. A simple, economical, and reliable system was established by using this two-fiber unidirectional optical channel switched ring configuration. To enable fast recovery of the optical channel, switching is performed automatically between a working optical channel and a protection optical channel at the destination node when triggered by a loss of signal (LOS), a loss of frame (LOF), or signal degradation (SD). The switching time is less than 50 msec in all cases. When a failure occurs, the agent detects alarms and masks redundant alarms. The agent then sends masked alarms to the element manager (EM) and alarm information to other agents. The EM determines which alarm from the agent is most critical and turns on the fail indicator on the failed packages.

*Dynamic Configurable Ring for the KomNet Field Trial*

The Berlin metropolitan backbone network consists of two interconnected DWDM rings belonging to different vendors [21]. Each ring is connected to a transparent long-haul link. Three add/drop multiplexers form one of the rings. The ring interconnection is realized by means of optically transparent interfaces, and it connects equipment of different vendors. Due to their optical transparency, these rings provide the opportunity to integrate telecommunication and data networks. Each ring in the Berlin metropolitan area network is around 60 km in circumference, and various access applications are supplied. One of these applications is Internet traffic using signal formats that are optimized for the WDM system (IP over WDM). The metropolitan parts are connected to the KomNet network, an optical network throughout Germany.

The flexible OADM supports both unidirectional and bidirectional traffic. The OADM consists of two stages: an add/drop stage and a distribution stage. The drop signals are extracted from the DWDM ring signal using optical circulators and tunable Bragg gratings. The system installed in the optical network in Berlin has 80 DWDM channels per fiber, a channel
Fig. 6.20 (a) Two-fiber unidirectional OADM ring system for L-band (prototype). (b) Reconfigurable OADM node.
spacing of 100 GHz, 16 channels per group, 3 nodes per ring, a ring circumference of 60 km, and a maximum optical path length of 100 km.

**PROMETEO Self-Healing Ring**

Two optical WDM metropolitan networks have been realized in the first phase of the Progetto Metropolitano di Telecomunicazioni Ottiche PROMETEO project [27]: one in Rome and one in Turin. The Rome network is a unidirectional ring in which both the protection and the add/drop functions of the optical channels are realized by optical devices. The Turin network is a modified SDH ring in which the add/drop function is carried out by SDH ADMs. Different architectures have been realized within the framework of the project to test the possibilities offered by optical networks (by the Rome ring) and the possibilities of using the existing SDH WDM technique.

As far as the Rome network is concerned, an important aspect of this trial is the integration in the same WDM network of OADM nodes produced by different manufacturers. It is a double unidirectional optical ring integrating three OADMs. Under normal operating conditions, the outer fiber is dedicated to clockwise WDM traffic and the inner fiber is reserved for protection. Four STM-16 channels (2.5 Gb/s) compose the WDM comb transmitted on the ring, and the nominal channel spacing is 6 nm. The normal wavelengths are 1536, 1542, 1548, and 1554 nm, and the tolerance of the carrier wavelengths is 2 nm. One of the OADMs is based on \(2 \times 2\) acousto-optic LiNbO\(_3\) waveguide switch technology, and the other is based on an interference multiplexer/demultiplexer composed of a cascade of four optical interference filters. The overall ring length is about 90 km, including a 40 km DSF and a 25 km SMF. The effects of the polarization sensitivity of the \(\lambda\)-switch and crosstalk were investigated. The reconfiguration time in the case of failure was measured and found to be about 24 msec (recovery time), demonstrating that this network architecture has a fast self-healing mechanism.

**NGI ONRAMP Testbed**

The next-generation multiwavelength (NGI ONRAMP) Internet optical network for regional access consists of a feeder network connected to end users via feeder access nodes and local distribution networks [28]. The feeder may typically cover a metropolitan area of 100 to 1000 square miles and contain 10 to 20 access nodes. Each distribution network may connect
100 or more business users at a bitrate of 1 Gb/s or more. The primary goal of ONRAMP is to enable research on the network transport of IP data over WDM regional access networks. To achieve this goal, ONRAMP functions as a reconfigurable WDM network capable of dynamic service provision, optical flow switching, and traffic load balancing. Service protection in the optical domain, medium access control protocols, and network control and management for transporting Internet traffic over the WDM network have also been investigated [28].

This network reconfiguration is made possible through the use of access nodes that contain both optical and electronic switching components, allowing data traffic to be routed all-optically through the network or to be switched and aggregated by electronic IP routers. The transmission of 16 ITU-T grid channels at data rates of up to 10 Gb/s is possible in this network. Preliminary demonstrations have been carried out by two high-end workstations that transfer TCP data using Gigabit Ether (GE).

6.4.4. WDM TECHNOLOGY

6.4.4.1. WDM-PON

Typical WDM-PON Configurations

The typical WDM-PON system configurations are shown in Table 6.4 [29, 30, 34, 35]. These are classified in terms of how the WDM wavelength is used. When the wavelength is assigned to each ONT, WDM filters (such as AWGs) are employed rather than an optical power splitter, as used in PON.

1. Wavelengths are assigned to upstream and downstream transmissions [22]. This type of WDM-PON corresponds to the B-PON, E-PON, GE-PON and G-PON. An optical power splitter is used.
2. Wavelengths for downstream transmissions are assigned to service provision [2, 3, 33]. This is the distribution and broadcasting of downstream signals. The desired signal is selected by the wavelength selector (tuner) at the ONT.
3. A downstream wavelength is assigned to each ONT and a unique wavelength is used for upstreams from all ONTs. For example, 1.3 µm is selected for the upstream transmission of each ONT by a WDM router [29].
Table 6.4 Typical WDM-PON Configuration.

<table>
<thead>
<tr>
<th>Configuration</th>
<th>Wavelength assignment</th>
<th>Features</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Downstream: 1.5 µm</td>
<td>-ATM-PDS</td>
</tr>
<tr>
<td></td>
<td>Upstream: 1.3 µm</td>
<td>-Power splitter</td>
</tr>
<tr>
<td>2</td>
<td>Downstream: λ1 ~ λn</td>
<td>Service multiplexing (broadcast, distribution)</td>
</tr>
<tr>
<td></td>
<td>-Assign to the services</td>
<td></td>
</tr>
<tr>
<td>3</td>
<td>Downstream: λ1 ~ λn</td>
<td>-Downstream: wavelength routing by WDM route</td>
</tr>
<tr>
<td></td>
<td>-Assign to the ONU</td>
<td>-Upstream: TDMA</td>
</tr>
<tr>
<td></td>
<td>Upstream: 1.3 µm (TDMA)</td>
<td></td>
</tr>
<tr>
<td>4</td>
<td>Downstream: λ1 ~ λn</td>
<td>-WDM Router</td>
</tr>
<tr>
<td></td>
<td>-Assign to the ONU</td>
<td>-User multiplexing</td>
</tr>
<tr>
<td></td>
<td>Upstream: λ1 ~ λn or λn + 1 ~ λ2n</td>
<td></td>
</tr>
<tr>
<td></td>
<td>-Assign to the ONU</td>
<td></td>
</tr>
</tbody>
</table>

4. Wavelengths for downstream and upstream transmissions are assigned to each ONT [5, 31, 32]. There are two cases: one where the downstream and upstream wavelengths are different, and the other where they are the same. WDM filters are used for multiplexing and demultiplexing in this WDM-PON.

Novel WDM-PON system configurations are summarized in Table 6.5. To reduce system cost, desired wavelengths are selected from among the WDM wavelengths generated simultaneously by multiwavelength light sources, and WDM sources are located only in the OLT, not in the ONT. They are classified as follows:

1. Desired wavelengths are assigned to a time slot that corresponds to each ONT. These time slot-dependent wavelengths are realized through the use of a modulator and a wavelength switch. In this case, the multiwavelength sources are used to generate WDM light sources.
2. All ONTs use the same spectrally broad multiwavelength source, which is realized by the amplified spontaneous emission (ASE) of optical amplifiers, a supercontinuum (SC) light source, and an LED. The ONT signal, whose wavelength is assigned to each ONT, is selected and multiplexed by the WDM router and transmitted through the fiber. This signal is demultiplexed by the WDM filters and received at the OLT. The wavelength selection realized by using the WDM router employed in this configuration is a spectrum-slicing
technique. It is advantageous in that light-source wavelength control becomes unnecessary in the ONT.

3. An optical loopback is used in WDM-PON. A portion of the downstream light is used to carry the data upstream. Instead of having a light source in the ONT, the modulator applies the modulation for the upstream light divided from downstream light. The reflection mirrors of the modulator or circulators are used to obtain the upstream light. Spectrum-slicing techniques are also introduced to generate the multiwavelength source in the OLT.

Other WDM-PON configurations consisting of WDM light sources and WDM routers have been described. Examples include a system configuration for optimum power splitter allocation and tandem connection [36], a configuration for upgrading PON systems already used at 1.3 µm [37], a service multiplexing configuration that uses wavelength-band multiplexing [38], configurations centered on the WDM light source in OLT that utilize a multiwavelength light source and spectrum-slicing techniques [6], a configuration designed to increase the number of users supported by AWG serial connections [39], a configuration providing WDM light-source generation from an LD chirped pulse [40], a WDM routing configuration utilizing the fast TDM wavelength packet assigned for ONT [32], and a cyclic-frequency AWG router for mesh path connection [41]. Several of the previous attractive configurations are described subsequently.

**Time Domain Wavelength Packet Multiplexing**

WDM packet routing is an attractive technique that will provide a high level of wavelength utilization in future access networks. WDM optical packets assigned for each ONU have been reported. This is shown in Figure 6.21. The 100 GHz spaced 16 channel WDM optical packets were generated by a super structure-grating (SSG)-DBR laser and

![Fig. 6.21 Time domain wavelength packet switching.](image-url)
transmitted through fiber at a line bitrate of 2.4 Gb/s and a packet length of 2 Kbytes. The network comprises an OLT, a wavelength router (WR), an ONU, a transmission line, and linear repeaters. The WDM optical packets are generated at the OLT by a fast tunable light source (SSG-DBR-laser) [4], modulated by a stream of data packets multiplexed in the time domain. The wavelength of each packet is set at the wavelength of the WR output connected to its destination ONU. The arrayed waveguide grating (AWG) is used as a WR. The modulated data packet is then transmitted over the fiber by optical amplifier repeaters and demultiplexed by the WR. The demultiplexed data packets are received at the ONU, and the original data are recovered. The period of each packet was 113 µsec and the capacity of each wavelength was 144 Mb/s. To avoid the transient effect of the SSG-DBR laser at the frequency switching point, a 463 nsec (144 bytes) guard-time interval was inserted between packets.

**Spectrum-Slicing Technique for WDM Light Sources**

Spectrum-slicing approaches are attempted to emulate WDM transmission cost-effectively by exploiting the fact that if spectrally broad sources (e.g., LEDs and ASE sources) are connected to one port of a WDM filter, only the sliced part of each source spectral output that falls within the port’s passband will pass through the WDM filter [6]. This is shown in Figure 6.22. The spectrally broad sources are individually modulated.

![Fig. 6.22 Principle of spectrum slicing.](image-url)
and then multiplexed, with each unique slice transmitted through a feeder fiber to be demultiplexed into spectral channels at a remote node. This is a trade-off in the channel between power, dynamic range, and WDM wavelength alignment accuracy.

The transmission of spectrum-sliced WDM access influenced by adjacent crosstalk has been estimated [42]. The experimental configuration is shown in Figure 6.23. A spectrally broad ASE radiating from an ONU travels through a 10 km fiber. Each ASE is spectrally sliced and multiplexed by an AWG filter in a remote terminal. The multiplexed signals are amplified and pass through a 50 km dispersion-shifted fiber (DSF). The transmitted light is fed to a central node, where the signals are multiplexed and detected. A 15 GHz wide, 25 GHz channel spaced 155 Mb/s × 32-channel transmission through 50 km DSF was achieved.

**Cyclic-Frequency AWG Routing**

A 32 × 32 full-mesh WDM network has been reported that uses a cyclic-frequency arrayed waveguide grating (AWG) router [41]. This realizes mesh path connection, although the physical topology is star or PON. The cyclic-frequency AWG router is passive and is located in the center node. In contrast, the remote nodes are equipped with WDM sources, which correspond to the destination nodes. The signals, which are assigned a specified wavelength, are transmitted from the remote node to the center
node through a fiber and are then routed into the corresponding outlet for the destination node. The $32 \times 32$ uniform-loss cyclic-frequency AWG router consists of a monolithically integrated $32 \times 64$ AWG and thirty-two 3 dB couplers. The $32$ wavelength WDM data with a channel spacing of 0.8 nm on the ITU-T grid and introduced into an inlet of the $32 \times 64$ AWG are routed into the corresponding outlets. In this experiment, $32 \times 32 (1024)$ paths are realized by only 32 wavelengths, and all 1024 paths transmit GE and 10 Gb/s data over a 10 km radius without optical amplifiers. Two fibers are used for upstream and downstream transmissions.

### 6.4.4.2. OADM Ring Scheme for Flexible and Simple Networks

Metropolitan ring architectures have been investigated with regard to developing flexible and simple cost-effective networks. The features consist of a centralized light-source configuration for reliability, the use of a multiwavelength light source and spectrum-slicing technique, and a passive OADM ring without optical amplifiers, for cost effectiveness.

**Flexible Metropolitan WDM Ring**

A transparent WDM metropolitan ring architecture has been described, in which optics enables the simultaneous provision of dedicated wavelengths for high-end users, while low-end users share wavelengths on a virtual ring [43]. The ring configuration is shown in Figure 6.24. Although high-end customers should benefit from the capability of establishing multigigabit per second direct optical connections, the associated cost of optical transmission equipment may be prohibitive for customers with lower demand levels. The feeder network is extended to a ring serving multiple access nodes (ANs); a packet format can permit multiple users to share a single wavelength instead of requiring a single wavelength per user, and a low-cost semiconductor optical amplifier (SOA) is used as a customer’s modulator, which operates as both modulator and amplifier. All wavelengths are generated at the network node (NN), that is, the center node (CN). Users served by AN1 are connected by a subring and share an NN wavelength. Users served by AN2 are connected in a star configuration and use distinct wavelengths. NN wavelengths are dropped from the ring and, after traveling to a user end station (ES), are reinjected into the ring.
at an access node (AN), which in its simplest form can be composed of a single $2 \times 2N$ port waveguide-grating router (WGR).

The effectiveness of the ring systems were confirmed experimentally by using 120 km conventional single-mode fiber at 622 Mb/s, with two ANs and an NN [43]. These were separated by 40 km fibers. At each AN, the light entered a $2 \times 16$ WGR, with a 50 GHz channel spacing, and was demultiplexed and distributed to an end station. Each ES included a polarization-insensitive ($<1$ dB) 1.5 µm SOA, and the electrical data signals were preequalized to compensate for the frequency response of the SOA/modulator.

**Simple Photonic Access Ring**

A novel node configuration using an SOA as a wavelength channel modulator has been reported with a view to realizing low crosstalk and good optical stability. The wavelength channel modulator (WCM) for an access ring consists of fiber Bragg gratings (FBGs) and an SOA, as shown in Figure 6.25 [45]. In this case, two circulators, two FBGs with the same reflection wavelength, an optical isolator, and an SOA are used in WCM. The WCM can operate in the same way as an OADM for a specific wavelength. Two kinds of interchannel crosstalk generated by the WCM have been estimated. One type occurs at a WCM that drops and modulates the...
specific channel $\lambda_1$. A small portion of the channel $\lambda_1$ that is transmitted through the FBGs and the isolator contributes this crosstalk. The other type occurs at the nodes that transmit the channel $\lambda_1$. A small portion of the wavelength channel $\lambda_1$ is unintentionally dropped, amplified (and modulated) by the SOA and inserted. The power penalty is calculated to be 0.29 dB when there are 40 nodes in the network. The BER and the effects of crosstalk have been experimentally estimated, and the penalty increase due to the crosstalk is negligible. In this experiment, two lights were used with wavelengths of $\lambda_1 = 1551$ nm and $\lambda_2 = 1558$ nm. The channel $\lambda_1$ was dropped, modulated by the SOA at 622 Mb/s, and inserted. The channel $\lambda_2$ was transmitted through the WCM.

6.4.4.3. WDM System Configurations Using TRPs

One cost-effective approach for WDM transmission is CWDM/wide-passband WDM technology, which relaxes the required wavelength setting accuracy of LDs and filters for WDM. WDM transponders (TRPs), which consist of WDM-Tx and Rx for WDM transmissions, and optical or electrical interfaces for intraoffice transmission, are used to transmit the various signals and formats, such as SDH and Ethernet. This is important in terms of increasing the flexibility and transparency for access and metropolitan area networks. The operation systems and equipment of the current systems do not need to be redesigned for WDM-TRP systems. This is the advantage of introducing WDM-TRP systems into today’s networks.
The system configurations used for WDM-TRP are shown in Figure 6.26. The point-to-point and ring configurations are constructed using TRP, as shown in Figure 6.27. The WDM-TRPs for SDH and for GE operate with four wavelengths (1.53, 1.55, 1.57, and 1.59 µm), which are bi-directional—1.53 and 1.57 µm for upstream transmission, and 1.55 and 1.59 µm for downstream transmission—over one fiber [46]. Dielectric filters with flat wide-passbands of about 15 nm are used. Because the DFB-LDs are installed in the TRPs without temperature control, the wavelengths of both TRPs exhibit a temperature variation of around 0.1 nm/degree in the 0 to 50°C range. The loss budget is 33 dB at 155 Mb/s for SDH, and 22 dB at GE. Single-mode fiber transmission over 80 km has been confirmed for both SDH and GE, and this distance is limited by the loss budget, not by dispersion in the fiber. The intraoffice system uses 1.3 µm wavelength Tx and Rx for SDH and 1000Base–SX at 0.7–0.85 µm for GE.

Fig. 6.26  Fundamental configuration of TRP.

Fig. 6.27  Application of WDM transmission for access and metropolitan area networks.
A system has been reported that simultaneously provides CATV video transmission and IP by means of Ethernet direct transmission [2]. The system configurations and wavelength allocations are shown in Figure 6.28. The CATV video signals are assigned to 1.55 µm, which is an appropriate wavelength for EDFA. The upstream and downstream IP signal transmissions are also assigned to 1.53 and 1.57 µm in one fiber. This system employs a DFB-LD without temperature control, except for CATV video transmission, and wide passband filters with cutoff characteristics of 3–5 dB/nm. The allowable crosstalk from CATV signals to IP signals is important, because high optical-power analog CATV signals are launched into the fiber. The crosstalk from CATV video signals is improved by using a double-stage WDM filter in DEMUX. In contrast, by measuring CNR, CSO, and CTB it was found that the influence of crosstalk from IP signals to CATV video signals is negligible.

Various WDM technologies and related devices have been developed, and new wavelength multiplexing/demultiplexing schemes are being employed. As regards CWDM/wide-passband WDM for access networks, the WDM wavelength regions are being expanded, and the number of wavelengths is being increased in accordance with required services and technical innovations. Because a WDM is now being used for the 1.5 µm

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**Fig. 6.28** Service multiplex system using WWDM.
C and L band region, the 1.3 μm wavelength region (O band) is utilized for the next stage. The wavelength number will be increased from 4–8 to 16 through these regions. And WDM technology is moving toward hybrid schemes involving CWDM/wide-passband WDM integrated with DWDM, and CWDM/wide-passband WDM integrated with super DWDM, where the wide CWDM/wide-passband WDM passband is used as the multiplexing/demultiplexing band. Figure 6.29 shows the trend in WDM schemes.

### 6.4.4.4. Packet over WDM

Various techniques have been reported for transmitting data packets over WDM. These techniques are used for access and metropolitan area networks, as well as core and photonic networks. One of the packets over WDM techniques for access and metropolitan areas is the hybrid optoelectronic ring network (HORNET) [5], which is a future MAN optimized for data traffic to provide efficient bandwidth sharing among a large number of access points (APs) in a metropolitan area. HORNET eliminates the cost and complexity of SONET/SDH equipment, by transmitting IP/ATM packets directly over the WDM layer. Three key components have been developed to improve performance:

- A novel carrier-sense multiple-access with collision avoidance (CSMA/CA) media access control (MAC) protocol
6. Optical Access/Metropolitan Area Network Using WDM

- Fast wavelength-tunable transmitters
- Fast clock and data recovery using the embedded clock tone (ECT) technique

These techniques make it possible to perform fast tuning with low overhead, transmit packets over the multiple-access network without collisions, and quickly recover clock and data using the ECT technique.

The CSMA/CA protocol is implemented using subcarrier multiplexed (SCM) headers. This is shown in Figure 6.30. Each wavelength in the network has a unique subcarrier frequency associated with it. When an AP transmits a packet on a particular wavelength, it multiplexes the wavelength’s corresponding subcarrier tone onto the packet. As the packets travel around the ring, they carry with them the SCM header, which indicates the presence of a packet on the wavelength at that instant. The presence of a subcarrier at a particular frequency tells the AP that the corresponding wavelength is currently unavailable. The transmitter uses the wavelength availability information to determine when to send a packet. The tunable transmitter consists of an Altitun’s GLSR laser tuning controller. The laser has three current-controlled tuning sections: a coupler section, a reflection section, and a phase section. A particular combination of currents at the three inputs corresponds to a particular output wavelength. According to the request of wavelength number, a programmable

![Fig. 6.30 Subcarrier header in HORNET.](image-url)
logic device (PLD) uses a lookup table to convert the incoming wavelength number to three particular digital values. Those digital values are passed into digital-to-analog converters (DACs) that convert the digital values to the associated analog current values, which are applied to the three tuning inputs of the laser.

6.4.4.5. SCM over WDM

SCM transmission over WDM wavelengths has been investigated with the goal of increasing transmission capacity and providing multiple services. Typical approaches can be categorized as follows. An application for transmission between a wireless center station and remote stations for mobile communications [47], optical routing of amplitude multilevel modulated SCM signals in a WDM access network [48], and multimodulation format signal integration, including SCM transmission by WDM [2, 49]. These approaches use CWDM/wide-passband WDM to assign the SCM video signal and additional service signals.

To reduce the system cost by sharing the transmitting and processing equipment and to simplify the architecture, a full-duplex WDM/SCM fiber-radio access network has been developed [47], featuring three WDM carriers for downstream transmission and a single carrier for upstream transmission. This is shown in Figure 6.31. Each downstream wavelength carries three 155 Mb/s BPSK SCM channels, and the upstream wavelength carries a 20 Mb/s BPSK RF channel. The mm-wave signals in the downstream fiber links are unaffected by chromatic dispersion. The network demonstration incorporates a 40 km SMF and 5 m radio cells. In the downstream direction, three lasers operating at 1537.5, 1541.5, and 1549.5 nm are used, each wavelength is externally modulated by three SCM mm-wave signals, and dispersion effects are overcome by optical single-side band (SSB) modulation.

6.4.4.6. OCDM over WDM

Optical CDM techniques incorporating WDM schemes have been investigated. They include an approach designed to suppress the optical beat interference in a WDMA network using subscriber-based common wavelength signaling or PON [50, 51], the use of the OCDM channels within an access node assigned a specific WDM wavelength [52, 53], and the use of photonic IP routing for optical codes [54], with both electric and optical
CDM techniques. Furthermore, four-channel WDM/OCDMA experiments on quaternary phase coding by using superstructured fiber Bragg gratings for coding and decoding [55], and a bidirectional OCDMA field trial system have been reported [56]. In the trial, a fully operating bidirectional OCDM system was demonstrated operating at 155.52 Mb/s per channel in the upstream and downstream directions over a 20 km SMF within the access part of the German KomNet field trial. CWDM is used to combine the four OCDM signals with other optical signals in DWDM channels of the metro ring.

A novel OCDM/WDM access network has been demonstrated [53], in which several OCDM channels share the same wavelength channel. The wavelength channel is first added/dropped at the node (ADM), and thus,
only the OCDM access protocol with tee and go capacity can be exploited without using complicated WDM access protocol. Access station #1, which is connected to the added/dropped node (ADM #1), is assigned an optical code (OC1), so that it can communicate with the other stations on the assigned wavelength ($\lambda_1$) via OCDM access protocol. To communicate with an access station on a different wavelength, the message must be on the destination wavelength. This approach makes it possible to take advantage of the asynchronous access of OCDM without using WDM access protocols. Figure 6.32 shows the OCDM/WDM access network.

6.5. Future Networks for Access and Metropolitan Areas

6.5.1. NETWORK IMAGE AND ITS REQUIREMENTS

Because various services and systems have appeared in access networks, including wireless, metal, HFC, and FTTH systems, the networks are characterized as access, metropolitan area, and core networks with their own requirements. Figure 6.33 shows an image of networks utilizing WDM. Access networks must be cost effective and flexible to provide various service that is transparent. WDM is used for service integration and user integration. Cost-effective CWDM/wide-passband WDM is promising. Star configurations, namely passive double-star (PDS) and single-star (SS) topologies, are mainly used. Metropolitan area networks must be flexible
in terms of increases in traffic and the provision of additional services. Moreover, these networks must be simple. The potential for capacity increase and user integration is important for WDM. A ring configuration is also used, as well as point-to-point transmission. Various WDM schemes, such as DWDM and CWDM/wide-passband WDM, have been introduced. The edge nodes in metropolitan area networks are important because they select the traffic from access networks to send to the service networks. In contrast, large capacity, simplicity, and reliability are important for the core networks, and WDM is expected to achieve these requirements. DWDM and super DWDM are used to increase capacity, and wavelength routing is also expected to be used to realize simple networks.

6.5.2. WAVELENGTH UTILIZATION

Practical networks utilize the WDM wavelength as a substitute for optical fibers. For example, the WDM wavelength is used mainly to increase core network capacity. The WDM wavelength is expected to provide flexibility and cost effectiveness in access and metropolitan area networks for various types of service and customers. WDM routing is also expected for photonic networks. Figure 6.34 shows typical cases in which the WDM wavelength is utilized. The wavelengths are used for large-capacity virtual fibers, service integration, and user integration.

Furthermore, wavelength-based traffic control, namely variable bandwidth, is expected in metropolitan area networks. This will be realized
(1) Large capacity

Transmission equipment

(2) Service integration

(3) User integration

(4) Wavelength routing

(5) Dynamic traffic and path control

by assigning a wavelength to a specified path when its traffic increases or decreases. The desired transmission capacity can be obtained flexibly by utilizing a wavelength path.

6.5.3. COST-EFFECTIVE APPROACH

Because the main growth is Internet-based services, such as content distribution, data networks will play an important role in the next generation of networks. For access networks, it is most important to realize cost effectiveness and flexibility for various services, which include IP-based services, existing telephony, and CATV. One way is to utilize large-scale markets and cost-effective technologies such as LAN. Another is to reduce the cost of DWDM based on conventional trunk and core networks. A third approach involves supplying various user interfaces for data networks, such as Ethernet. Cost effectiveness is critically important in WDM technology. Optical components, such as optical filters and LD modules, are particularly important in terms of reducing the cost of WDM transmission. Several technologies have been investigated, such as PLC and
polymer-based filters, dielectric thin films for filters, passive alignment, and plastic modules.

6.6. Standardization

The standardization organizations related to WDM technology and systems are International Telecommunication Union-Telecommunication Standardization Sector (ITU-T), Institute of Electrical and Electronics Engineers-802.3ahEFM (IEEE 802.3ahEFM: Ethernet in the First Mile), and Full Services Access Networks (FSAN). ITU-T is concerned with carrier networks; IEEE and FSAN are concerned with de facto standards. Figure 6.35 summarizes the current status of WDM standards. ITU-T recommends a 100 GHz spacing for medium- and long-distance DWDM transmission, and a 200 GHz spacing for metropolitan ring networks, with a standard

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<th>(1) ITU-T</th>
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<tr>
<td>(a) Metro NW</td>
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<tr>
<td>- DWDM: G.dapp (point-point); Under discussion</td>
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<tr>
<td>wavelength grid: 200, 100, 50, 25, 12.5 GHz (G.694.1)</td>
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<tr>
<td>10 Gb/s NRZ, 2.4 Gb/s NRZ</td>
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<tr>
<td>- CWDM: G.695 (point-point)</td>
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<tr>
<td>wavelength grid: 20 nm between 1291–1611 nm (G.694.2) with 4, 8, 12 &amp; 16 channels</td>
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<tr>
<td>2.4 Gb/s NRZ, GE</td>
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<tr>
<td>(b) Access NW</td>
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<tr>
<td>- B-PON: G.983 series (Contributed by FSAN)</td>
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<tr>
<td>stream multiplexing: G.983.1</td>
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<tr>
<td>1310 nm for upstream and 1530 nm for downstream</td>
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<tr>
<td>stream and service multiplexing: G.983.3</td>
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<tr>
<td>1310 nm for data upstream and 1490 nm for data downstream</td>
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<tr>
<td>1550 nm for video distribution</td>
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<tr>
<td>- G-PON: G.984.2 (Contributed by FSAN)</td>
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<td>The same wavelength allocation as G.983.3</td>
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<td>- 100 Mb/s MC: G.985</td>
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<td>The same wavelength allocation as G.983.1</td>
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<th>(2) IEEE802.3</th>
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<tr>
<td>- GE-PON: 1000BASE-PX</td>
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<tr>
<td>The same wavelength allocation as G.983.3</td>
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<tr>
<td>- 100 Mb/s MC: 100BASE-BX</td>
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<td>The same wavelength allocation as G.983.1</td>
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Fig. 6.35 WDM standardization.
frequency of 192.1 THz. Discussions related to CWDM started in February, 2001 (ITU-T: G.694.1). The ITU-T recommended the wavelength spacing of 20 nm in the O to L band with 18 channels (ITU-T: G.94.2). However, another channel spacing of 24.5 nm is also used for the O band, as well as 20 nm channel spacing. These wavelength allocations are expected to provide cost effectiveness. ITU-T/FSAN is concerned with service multiplexing by WDM, which is based on ATM-PON. The ATM-PON already uses the 1260–1360 nm wavelength region for upstream transmissions, and the 1480–1580 nm region for downstream transmissions (ITU-T: G.983.1). New wavelength allocations include a wavelength for video use in the 1550–1560 nm region, and a wavelength for digital use in the 1539–1565 nm region as an enhancement band. Downstream transmission is assigned to the 1480–1500 nm range. Certain bands will be reserved for additional, future services. This is shown in Figure 6.36. The FSAN wavelength allocation is recommended in ITU-T G.983.3, March, 2001. In contrast, the standardization of LAN and WAN with Ethernet is discussed in IEEE 802.3. WDM technology is proposed for parallel transmission and discussed with a view to achieving 10 GE transmission at a reasonable cost.

ITU-T also established a new category for optical fiber for WDM transmission, describing this in recommendation G.655 in 1996. The title of

![Fig. 6.36 Wavelength allocation of B-PON.](image)
recommendation G.655 is *Non-Zero Dispersion Shifted Fiber (NZDSF)*. The dispersion value $D$ lies in the $0.1 \leq |D| \leq 10$ range, for wavelengths of 1530–1565 nm. This fiber can suppress the nonlinear effects of FWM in a WDM transmission. The ITU-T recommendations for optical fiber are as follows:

1. G.652: Single-mode fiber cable (zero dispersion in the 1300 nm region)
2. G.653: Dispersion-shifted fiber cable (zero dispersion in the 1550 nm region)
3. G.654: Cut-off shifted fiber cable (minimum excess loss in the 1550 nm region)
4. G.655: Non-zero dispersion shifted fiber cable (WDM transmission in the 1530–1565 nm region)

### 6.7. Trends in Access and Metropolitan Area Networks

Access and metropolitan area networks are changing, with increases in various services and the continuing development of optical technologies. Networks that can provide appropriate service features are becoming important. Traffic from access networks is routed into service networks at the edges of the metropolitan networks. Various network topologies and WDM schemes are expected to be introduced into the networks. The wavelength region has expanded and the wavelength number increased through the use of WDM wavelengths. New technologies, such as signal processing and wavelength conversion, are expected to have an impact on network configurations. These trends are shown in Figure 6.37.

### 6.8. Conclusion

This chapter has described WDM technologies and networks, ranging from related devices to network systems in access and metropolitan area networks. With regard to access networks, the focus has been on achieving cost-effective WDM approaches and flexibility for various services, such as WDM schemes (DWDM, CWDM, wide-passband WDM, wide-WDM [1.3/1.5 $\mu$m]), PON architecture, and WDM integration. With regard to
metropolitan area networks, the focus has been on OADM ring systems and related technologies. Typical field trials and experiments of WDM systems were also described. We can expect new WDM network configurations to be developed for future data networks through the utilization of WDM wavelengths.

References


Chapter 7  
A Wavelength-Division-Multiplexed Optical Network for Video/Audio Signal Distribution in a Broadcast Center

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7.1. Introduction

Video-signal routing networks in television broadcasting stations have recently been undergoing a process of total digitalization. Such networks are required to handle more than 200 uncompressed, serial digital video signals, whose speed is in the hundreds of megabits per second. To meet such demands, optical technologies have been shown to offer great promise for increasing both the capacity and the flexibility of networks [1]. Optical transmission technology has been utilized on a point-to-point basis from the early stages of digitalization of broadcast centers. To benefit fully from the advantages of optical technologies, a completely different type of routing network structure is necessary. From this viewpoint, a wavelength-division and time-division (WD/TD) hybrid multiplexed optical network for application in a television broadcast center has already been proposed [2]. This type of optical network is attractive for application in a broadcast center, because of its large capacity, ability to handle multiple formats, and flexible operation capabilities.

This chapter describes the design concept, system structure, and performance of the proposed optical network. Section 7.2 reviews the requirements for a signal-routing network in a contemporary broadcast center.
Then, Section 7.3 describes the structure and features of the developed WD/TD optical network. The design concept of the network is presented in Section 7.4. Finally, Section 7.5 explains the development of the facilities in Fuji Television’s broadcast center, where the developed network is implemented. To the authors’ knowledge, this is the world’s first practical implementation of an optical network in a broadcast center.

7.2. Requirements for a Signal Routing Network in a Contemporary Broadcast Center

Figure 7.1 shows an overview of a typical signal-distribution system in a broadcast center. A variety of facilities are connected to each other via a video/audio-signal routing network. This network is one of the most important support systems for operations, such as program making, carried out at a broadcast center. The television industry is moving toward higher-quality program production and distribution. For this purpose, the digitalization of broadcast center systems has been progressing. The routing network within a broadcast center in this digital era is required to be more versatile than conventional analog systems. It must accordingly satisfy the following requirements:

- **High speed and wide bandwidth:** Even in the standard NTSC composite signal format, the signal speed of an uncompressed digital

![Fig. 7.1 Broadcast center system for distributing digital video signals.](image-url)
signal reaches as high as 143 Mb/s. The signal speed of component and high-definition (HD) TV signal formats range from 270 Mb/s to 1.485 Gb/s.

- **Multiple-format capability:** Even at present, there are many TV broadcasting formats, such as SD (standard definition), ED (enhanced definition), and HD (high definition). In the future, new kinds of formats, including compression formats such as MPEG (Moving Picture Experts Group) will be added. Distribution networks in future full-HDTV studios using these broadcasting formats must be flexible.

- **Flexibility in operation**

- **Large capacity and potential for gradual expandability**

Conventional signal-routing networks utilize electronic routing switchers, as shown in Figure 7.2. Video/audio signals are fed into the routing switcher. Although there are a lot of video/audio signal sources, only some signals selected by the routing switcher are sent to destinations. The routing switcher makes these selections or connections according to a predetermined schedule set by the control center. This centrally controlled operation puts a heavy workload on the operators in the signal-distribution center, especially during broadcasts of emergencies, such as disasters. Flexible operation with control from destinations would be desirable. In addition, the conventional electronic switching systems need a huge amount of hardware and power consumption to satisfy the previously mentioned

![Fig. 7.2](image-url) Conventional signal-routing network utilizing an electronic routing switcher.
requirements. Each signal format usually requires an individual switcher. High-speed digital transmission requires large, heavy coaxial cables as the transmission medium if standard electrical transmission technology is used.

To solve the preceding problems of conventional technologies, optical technologies are very attractive. Optical transmission can provide excellent performance in long-distance transmission of high-speed serial digital signals. An optical fiber is lightweight and flexible for wiring. Moreover, optical technologies have immunity against electromagnetic induction (EMI). Making use of these advantages, optical transmission technology has been utilized on a point-to-point basis from the early stages of digitalization of broadcast centers. However, to enjoy fully the advantages of optical technologies, a completely different type of routing-network structure is necessary. The next section will describe such an optical network structure.

### 7.3. Proposed WD/TD Optical Network

Figure 7.3 shows the structure of the network we originally proposed [2]. It consists of a central star coupler connected to local centers, which are located in studios and/or control rooms within a broadcast center. Serial digital video signals from various video sources are time-division multiplexed (TDM) into a high-speed signal at each local center. Each local center transmits the TDM signal to the star coupler at a unique wavelength. This signal is then wavelength-division multiplexed (WDM) with the signals

![Fig. 7.3 Wavelength-division and time-division (WD/TD) hybrid multiplexed optical network.](image-url)
from other local centers. The WD/TD hybrid multiplexed signals from the star coupler are then transmitted to all of the local centers. At each local center, individual video signals are selected from the WD/TD signals by using tunable wavelength filters and TD channel selectors.

This type of network has three important features. First, the use of WDM in combination with TDM allows the network to handle a large number of video signals on a relatively small number of WD and TD channels; in other words, a practical system can be produced at present levels of optical technology [3]. Second, each local center can freely and directly access all video signals within the network. This allows flexible operation control at various places in a broadcast center and a reduction of the operator workload in the signal-distribution center. Finally, the fact that signals are transmitted from local centers on individual unique wavelengths allows the system to handle simultaneously a variety of different video signal formats, including NTSC, PAL, EDTV, and HDTV. The design is thus both practical to achieve and extremely flexible in its operation.

By using several sets of the basic network structure, as shown in Figure 7.3, a larger-scale and more flexible routing network is possible [4]. An example of such a network is given in Figure 7.4. This structure uses two WD/TD optical networks together with $2 \times 1$ photonic switch matrices [5].

**Fig. 7.4** Network structure using two sets of WD/TD optical network with $2 \times 1$ photonic switches.
Two sets of WD/TD hybrid multiplexed optical signals are distributed via two optical fiber cables to receiver units located in studios or control rooms. At each receiver unit, the required video signals can be selected by using tunable wavelength filters and TD selectors, after selecting one star-coupler system out of two by using $2 \times 1$ photonic switches. This structure enables the number of video/audio signals to be increased simply by adding star coupler-based WD/TD optical networks in parallel. Therefore, a gradual increase in system capacity is possible. The use of two sets of WD/TD networks can enhance system redundancy and network capacity. Important signals can be transmitted by using both of the WD/TD networks. Therefore, system reliability can be improved without having to prepare special standby systems.

The signal speeds of NTSC composite and component signal formats are 143 and 270 Mbit/s, respectively. The currently available signal speed of optical transmission equipment at a reasonable cost is about 2.4 Gbit/s. Therefore, 16 signals can be transmitted using the NTSC composite signal format, and eight signals can be transmitted using the NTSC component format. To handle more than 200 channels, the number of WD channels for the composite signal format must be about 16. This number can be achieved in the low-loss wavelength region of optical fibers around 1550 nm. For the component signal format, a WD/TD optical network with 32 WD channels or two WD/TD optical networks, each of which utilizes 16 WD channels, can handle more than 200 digital video signals.

For the compressed digital video signals that are utilized in digital broadcasting, one optical transmitter using TDM, as shown in Figure 7.5, might be able to distribute enough video signals. Because the signal speeds of compressed digital video signals are up to about 10 Mb/s even in HDTV format, one optical transmitter can distribute more than 200 video signals. Because the signal speed of HDTV is 1.485 Gb/s, one WD channel should be assigned for an HDTV signal.

The alternative approach for the design of the optical receiver unit in a local center is illustrated in Figure 7.6. The WDM signals are separated by a wavelength-division demultiplexer and converted into electrical signals by optical receivers. The routing function is performed using an electronic switch matrix. The desired signal can be obtained by using a time-division demultiplexer-selector placed after the switch matrix. In this approach, the signal speeds of the optical signals should be the same. To meet this requirement, it is proposed that all TDM signals use the synchronous digital hierarchy (SDH) format [6].
7. A Wavelength-Division-Multiplexed Optical Network

Over 200-ch compressed Digital Video/Audio Signals with MPEG2 format (about 10 Mb/s)

Fig. 7.5 An example of a network structure for distributing compressed digital video or audio signals.

Fig. 7.6 Alternative optical receiver unit structure using a wavelength-division demultiplexer and an electrical switch matrix.
7.4. Network Design

7.4.1. WDM SYSTEM

The system margin degradation caused by WD channel selection in our network can be attributed mainly to two effects [7]:

- Linear crosstalk from the other WD channels
- Passband width of the tunable wavelength filter (namely, the transmitter spectrum deformation due to the limited passband width of the tunable optical filter may cause an excess loss and a power penalty)

The power penalty owing to these effects can be calculated by simulating the eye pattern degradation [8].

Figure 7.7 shows the steps of the method for simulating the eye pattern. The change of signal, when passing through an optical filter, is calculated in the frequency-domain. First, a proper electronic modulation waveform [in this case, a $2^6$-1 PN (pseudorandom) pattern] is assumed. The optical spectrum of the optical transmitter output is calculated by using a parameter of the optical transmitter and the modulation waveform. The effect of the limited passband width of the tunable wavelength filter is taken into account in the frequency domain. Finally, crosstalk signals are added to the main signal, which pass the tunable wavelength filter. It is assumed that each crosstalk signal has the same optical power. Here, the ratio of the sum of crosstalk signal power to the main signal power is defined as total crosstalk value.

Experiments were also conducted to examine the effects mentioned previously. Figure 7.8 shows the experimental setup for examining (a) filter

![Fig. 7.7 Eye pattern simulation flow.](image-url)
passband effect and (b) crosstalk effect. To determine the filter passband effect, directly modulated LDs and external modulators were both used, together with tunable wavelength filters with various passband widths. In the crosstalk experiment, seven WD channel signals were added to the desired signal via a variable optical attenuator. Several experiments were carried out at a digital HDTV signal speed of 1.5 Gb/s.

Figure 7.9 shows the relation between power penalty and the ratio of filter bandwidth (f) to transmitter spectral width (l). Also shown in Figure 7.9 are experimental results [7]. The simulated results clearly agree with the experimental ones. The relation between excess loss and the ratio of filter bandwidth (f) to transmitter spectral width (l) is depicted in Figure 7.10. Again, excellent agreement between simulated and experimental results is obtained. These figures show that the following relation must be satisfied in order to suppress the system margin degradation due to the filter passband effect to a negligible value:

\[ f > 10l \]  \hspace{1cm} (7.1)
Fig. 7.9  Relation between excess loss and the ratio of filter bandwidth to transmitter spectral width ($f/l$).

Fig. 7.10  Relation between power penalty and the ratio of filter bandwidth to transmitter spectral width ($f/l$).
Figure 7.11 shows the calculated eye patterns (a) of the main signal without the crosstalk channel and (b) with 15 crosstalk channels (−5 dB total crosstalk). The power penalty calculated from the eye degradation, as a function of total crosstalk, is shown in Figure 7.12. When the number of crosstalk channels increases, the power penalty decreases, because the crosstalk channels interfere destructively with each other. In Figure 7.12,

![Eye patterns](image)

**Fig. 7.11** Calculated eye patterns: (a) without optical crosstalk and (b) with 15 crosstalk channels (total crosstalk value of −5 dB).

![Power penalty plot](image)

**Fig. 7.12** Power penalty from optical crosstalk.
the dots and the circles show the experimentally obtained power penalty values with one and with seven cross-talk channels, respectively. The calculated and measured power penalties agree well.

For suppressing the power penalty to less than 0.5 dB even in the worst case (one crosstalk channel), the total crosstalk power penalty must be less than $-13$ dB. The total crosstalk depends on WD channel separation ($d$), the number of crosstalk channels, and the filter passband spectra. If the filter passband spectra is assumed to be Lorentzian, the relation between power penalty and the ratio of WD channel spacing to filter passband width can be calculated as shown in Figure 7.13. This figure shows that the following condition must be satisfied in order to obtain a power penalty less than 0.5 dB:

$$d > 3.5 f$$  \hspace{1cm} (7.2)

To utilize a large number of WD channels, the WD channel spacing $d$ must be around 0.8 nm. In this case, according to condition 7.2, the filter passband width $f$ should be less than 0.23 nm. According to condition 7.1, transmitter spectra width under modulation should be less than 0.023 nm.

![Fig. 7.13 Relation between power penalty and the ratio of WD channel spacing to filter passband width $d/f$.](image)
Dielectric or Fabry–Perot (FP) type filters can be made to satisfy these conditions if external modulators are employed in the optical transmitters.

### 7.4.2. TDM SYSTEM

One way to achieve TDM in our WD/TD optical network may be to use the synchronous digital hierarchy (SDH) system, which is widely used in trunk-line systems. However, the SDH system seems to be too complicated and expensive for application in a TV broadcast-center network, because it contains an embedded OAM (operation, administration, and maintenance) system required in long trunk-line systems. Therefore, we use simple bit-by-bit TDM in the proposed WD/TD optical network.

Standardized digital video signals usually have a large variation in mark density [11]. The serial digital-interface system, defined as SMPTE 259M, is a non return to zero invert (NRZI)-based signal scrambled with a generation polynomial: \( x^9 + x^4 + 1 \). This scramble system is good enough for coaxial cable transmission for avoiding direct current or a very low-frequency component in the digital video signal and for keeping the run length short. However, we found that there is some difficulty in transmitting the SMPTE 259M serial digital-interface signal using AC-coupled optical transmission equipment, which is usually used in high-speed trunk-line systems. Moreover, the TD-multiplexing system used in the new WD/TD optical network might make this difficulty even worse, compared with a one-channel-transmission case.

To overcome this problem, we use another technique, based on a higher-order generation polynomial, to scramble the SMPTE 259M standard signal. Calculations were made to find the optimum generation polynomial, then it was found that the maximum run length can be suppressed to less than 20 when scrambling functions with a power higher than 15 are used. We use a scrambling system with a generation function \( x^{17} + x^3 + 1 \) for the input/output video signals of the TDM system.

To select the desired video/audio signal from a TDM signal, it is necessary to identify the start of the TDM frame. For frame synchronization, one of the TD channels is used as the frame identifier. The frame-identifier signal is set to be complementary to the adjacent TD channel. Doing so also reduces the variation in mark density. These functions can easily be performed by integrated circuits (ICs), because the main functions operate at the speed of serial digital video/audio signals (143 Mb/s for composite; 270 Mb/s for component NTSC signals), not at the high TDM signal speed.
The TDM system described here has already been submitted to the ITU-R as a candidate for standardization of digital video signal transmission using optical technology [12].

Optical transmission systems, presently available at a reasonable cost, have a signal speed of about 2.4 Gb/s. This means that the TDM highway speed should not exceed 2.4 Gb/s in order to keep the system cost down. We have chosen to use a 16:1 TD-multiplexer/demultiplexer (MUX/DEMUX) to transmit 15 channels of 143 Mb/s NTSC composite video signals, together with a frame identifier, by using one WD channel (TDM highway speed of 2.29 Gb/s), as shown in Figure 7.14a. For the component signal (270 Mb/s), 8:1 TD-MUX/DEMUX can be used to transmit seven video/audio signals together with a frame identifier. This results in a TDM signal speed of 2.16 Gb/s (Figure 7.14b).

Fig. 7.14 Various TDM systems applicable to the WD/TD optical network: (a) for NTSC composite signals, (b) for component signals, and (c) an NTSC composite signal system (which can handle composite signals by using two composite channels).
Although the speeds of the TDM signals are somewhat different, these signals, with different formats, can be integrated in the WD/TD optical network by using different WD channels. One component signal, with a speed of 270 Mb/s, can be transmitted by using two channels; each is prepared for a 143 Mb/s NTSC composite signal. A signal converter, which converts a 270 Mb/s signal into two 135 Mb/s signals, enables both NTSC composite and component signal formats to be TD-multiplexed with a 16:1 TD-MUX/DEMUX, as shown in Figure 7.14c. Because a signal speed of 1.485 Gb/s is too high for TDM, one WD channel is dedicated for one HDTV signal.

7.5. Practical Network Development

The world’s first optical network for a broadcast center was developed and implemented in Fuji Television’s new broadcast center in 1997. The network was designed to distribute about 150 channels of NTSC composite video signal and 15 HDTV signals. This section describes the design concept of the new broadcast center and the performance of the developed optical network [8–10].

7.5.1. NETWORK DESIGN

The specifications of the video/audio signal-distribution network of the new broadcast center are listed in Table 7.1. Fuji Television’s broadcast center is based on this specification.

<table>
<thead>
<tr>
<th>Requirements</th>
<th>Present</th>
<th>Future</th>
</tr>
</thead>
<tbody>
<tr>
<td>Transmission Format</td>
<td>NTSC Composite (143 Mb/s)</td>
<td>HDTV (1.5 Gb/s)</td>
</tr>
<tr>
<td>Number of Signals</td>
<td>NTSC</td>
<td>150</td>
</tr>
<tr>
<td></td>
<td>HDTV</td>
<td>15</td>
</tr>
<tr>
<td>Number of Destinations</td>
<td>20</td>
<td>&gt;50</td>
</tr>
<tr>
<td>Number of Outputs</td>
<td>150</td>
<td>&gt;200</td>
</tr>
</tbody>
</table>
Considering the WD channel selection characteristic of current tunable wavelength filters, we set the WD channel spacing to 1 nm. Although 32-channel WDM is possible within the Er$^{3+}$-doped fiber amplifier (EDFA) gain bandwidth, by employing a practical WD channel spacing of 1 nm, such a design would require WDM transmitters with wavelengths distributed over a significantly wide range of wavelengths (about 30 nm). Because these devices would be prohibitively expensive, we use two sets of WD/TD optical networks, each using 16 WD channels, as shown in Figure 7.4. This design can be used for distributing 480 channels of NTSC video signals or 32 channels of HDTV signals. The maximum throughput, therefore, reaches as high as 73 Gb/s.

As an optical transmitter, a DFB laser diode (LD), and an electro-absorption (EA) type optical modulator [13] are used. The filter we employed in the network was a Fabry–Perot type, and its crosstalk level at 1 nm from the transmission peak was less than $-18$ dB. As shown in Figure 7.4, each EDFA is inserted between an optical transmitter and a star coupler. This configuration allows the use of conventional and inexpensive EDFAs, which have been developed for single-channel amplification. In addition, the optical power variation among wavelength channels can be compensated for at the EDFA outputs by applying an automatic power control (APC) scheme to EDFAs. When the APC scheme is applied to EDFAs, the optical power budget from EDFA output to optical receiver

![Fig. 7.15 System diagram of the new broadcast center.](image)
Table 7.2 Optical Power Budget of Network.

<table>
<thead>
<tr>
<th>Description</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>EO Output (dBm)</td>
<td>0.0</td>
</tr>
<tr>
<td>EDFA Output (dBm)</td>
<td>14.5</td>
</tr>
<tr>
<td>Receiver Sensitivity (@10^{-9} BER, dBm)</td>
<td>-32.0</td>
</tr>
<tr>
<td>Allowable Loss (dB)</td>
<td>46.5</td>
</tr>
<tr>
<td>Worst case Optical Loss (dB)</td>
<td></td>
</tr>
<tr>
<td>16 × 64 Star coupler</td>
<td>20.0</td>
</tr>
<tr>
<td>1 km Optical fiber cable (including connectors)</td>
<td>2.0</td>
</tr>
<tr>
<td>1 × 8 Optical coupler</td>
<td>11.0</td>
</tr>
<tr>
<td>1 × 2 Photonic switch</td>
<td>1.0</td>
</tr>
<tr>
<td>Tunable wavelength filter</td>
<td>4.0</td>
</tr>
<tr>
<td>10:90 Optical coupler</td>
<td>1.0</td>
</tr>
<tr>
<td>Power Penalty (dB)</td>
<td></td>
</tr>
<tr>
<td>EDFA noise</td>
<td>negligible</td>
</tr>
<tr>
<td>Interchannel crosstalk</td>
<td>0.5</td>
</tr>
<tr>
<td>Total (loss + penalty, dB)</td>
<td>39.5</td>
</tr>
<tr>
<td>System Margin (dB)</td>
<td>7.0</td>
</tr>
</tbody>
</table>

must be considered. Table 7.2 lists the optical power budget for the network. Note that the system margin is as large as 7 dB even in the worst case.

The transmitters and two star couplers are located at the signal distribution center, and the signals are distributed to each destination using two optical-fiber cables, as shown in Figure 7.15. The receiver unit is designed so that it can be monitored through a conventional Ethernet-type local area network (LAN). The video/audio signal information is also processed in the LAN.

7.5.2. **PRACTICAL NETWORK IMPLEMENTATION**

Functional diagrams of the transmitter (TX) and receiver (RX) cards for NTSC video signals are shown in Figure 7.16 and Figure 7.17, respectively. For bit/frame synchronization, scramble/descramble, and TD-channel selection, two kinds of gate arrays using ECL technology are used. For the MUX/DEMUXs, GaAs ICs (each card measuring 380 × 270 mm) are used [14].
The TX card contains a dielectric multilayer optical filter, which is used for the wavelength reference. The temperature of the transmitter laser diode is controlled by a microcomputer (using the step-by-step method) in order to maximize the transmitted power of the reference filter [15]. Figure 7.18 shows the wavelength stability of the transmitter laser diode, which was measured by an interferometer-type wavelength meter (Advantest TQ8325) using a He-Ne laser as a reference. The wavelength stability, ±0.05 nm, is enough for a 1 nm spacing WDM.

Figure 7.19a and Figure 7.19b show output waveforms of the MUX and TD channel selectors, respectively. Figure 7.19a shows the 2.29 Gb/s TDM output waveform of the MUX when 15 143 Mb/s pseudorandom patterns,
Figure 7.18 Transmitter wavelength stability.

Figure 7.19 Output waveforms of (a) a TD multiplexer (MUX) and (b) a TD channel selector.

Together with a frame synchronization signal, are fed into its input ports. Figure 7.19b shows the waveform of a 143 Mb/s signal selected from a 2.29 Gb/s TDM signal. Both figures show clear eye openings.

The performance of the new network was evaluated in a 16-WD-channel transmission experiment using pseudorandom patterns at a signal rate of 2.29 Gb/s. The bit error rate was measured with a tunable wavelength filter after WD channel selection. Figure 7.20 shows the optical spectrum after the filter. The crosstalk levels at the adjacent channels are as low as $-18$ dB. The measured bit error rate is shown in Figure 7.21. The receiver sensitivities at the bit error rate of $1 \times 10^{-9}$ for back-to-back and after WD channel selection were $-32.0$ dBm and $-31.8$ dBm, respectively.
Fig. 7.20  Optical spectrum after signal passes through a tunable wavelength filter.
The power penalty resulting from 16-WD-channel simultaneous operation is as small as 0.2 dB.

A photograph of the system rack for the NTSC system is shown in Figure 7.22. Each TX, optical amplifier, and RX unit contains eight cards. A photograph of the operation room of the signal-distribution center is given in Figure 7.23. The system is operated by two personal computers. Figure 7.24 shows a photograph of the racks containing the star coupler and the optical amplifier, transceiver, and receiver in the signal distribution center. Each of two racks on the front side contains an optical transmitter unit, a star coupler, and an optical amplifier unit. The third rack consists of optical receiver units, each of which contains eight RX cards. These optical receiver units are used for monitoring the signals to be distributed in the broadcast center. The lightweight and flexible nature of the optical fiber cables, compared with coaxial cable, means that all the facilities in the new broadcast center are effectively downsized.
Optical Transmitter (TX) Rack
8 TX cards / Rack
# of signals / card :  15  (NTSC Composite)
    7  (Component)
    1  (Hivision)

Optical Amplifier Rack
8 Cards / Rack

16 × 64 Star coupler #1
16 × 64 Star coupler #2

Optical Cable: Single Mode Fiber

Optical Receiver (RX) Rack
8 RX Cards / Rack

Fig. 7.22  Photograph of network equipment.

Fig. 7.23  Operation room of signal-distribution center.
7.6. Conclusion

A WD/TD optical network, which is required to handle more than 200 uncompressed serial digital video signals with speeds of hundreds of megabits per second, was developed and implemented at a television broadcast center. This type of optical network is attractive for application in a broadcast center because of its large capacity, ability to handle multiple formats, and flexible operation capabilities. The network has been implemented as the world’s first commercial system at Fuji Television’s new broadcast center. The network is designed to distribute about 150 channels of NTSC composite video signal and 15 HDTV signals. To the authors’
knowledge, this is the world’s first practical implementation of an optical network in a broadcast center. Recently, other major Japanese broadcasters have installed the same kind of system.

The main problem concerning the application of optical networks in broadcast centers is the system cost. The system performance is being increased, and the cost of electronic equipment is rapidly decreasing. To take full advantage of the optical network described in this chapter, cost reduction of optical components is indispensable, because the cost of an optical network system depends mainly on the optical devices. It is well known that the device cost decreases rapidly as the amount of device production increases. WDM systems are expected to be used in wider areas in communication, such as metropolitan and access areas. With the cost reduction expected from such an increase in demand for WDM systems, the application area of the optical network explained in this chapter would expand.

Acknowledgments

The authors would like to express their gratitude to S. Horie, M. Nagata, C. Kamise, and S. Ando of Fuji Television and to H. Higashi and Y. Ushiyama of NEC Corporation, as well as to their colleagues who contributed to this work, for their continuous encouragement.

References


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Chapter 8 | WDM Computer Networks: A Survey

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8.1. Introduction

The past few years have witnessed an explosion in the computer industry, the growth in data traffic being one of the primary reasons. Consequently, the demand for bandwidth to accommodate data has been on the rise. With remarkable lasting power, Gordon Moore’s famous maxim—that computing horsepower doubles every 18 months—has defied several cycles of high-tech development. Now, however, Moore’s law is less than suitable for the new universe of connected computing. A new law is required to govern the pace of technology and its implications for our lives.

Fortunately, the same era has also witnessed the evolution of the optical fiber as the transmission medium of choice for high-speed communication. The vast bandwidth, coupled with incredibly low bit error rates, has contributed in large part to its success. With recent advances in optical technology, wavelength-division multiplexing (WDM) has been identified as one of the techniques that aim for effective resource utilization.

WDM is considered a promising transport mechanism for improving fiber bandwidth utilization in future optical networks [1, 2]. Demonstrations of current optical technology have shown a feasibility of up to 160 channels (wavelengths) per fiber, each operating at 10 Gb/s. WDM technology may

1 This work was funded in part by a grant from Cisco Systems and by NSF grant No. ANI-0322959. The authors may be reached by email at krishna@cs.umbc.edu.
be used in local, metropolitan, and wide area networks (LANs, MANs, and WANs).

The inherent advantages of WDM have made it the current favorite multiplexing technology for communication networks and, in particular, for optical networks. Today’s major carriers are devoting significant effort to the development and application of WDM technologies [3]. This chapter serves as a survey of WDM applications. It identifies computer networks in various arenas that use WDM and tries to illustrate the importance of WDM in networking applications by portraying various networks that deploy and gain from it.

The rest of the chapter is organized as follows. In Section 8.2, a brief introduction to WDM and WDM computer networks is presented. This section also discusses the economics benefits of using WDM. Sections 8.3 through 8.5 discuss the application of WDM to LANs, MANs, and WANs, respectively. The latest trends in the use of WDM are discussed in Section 8.6. Section 8.7 concludes the chapter.

8.2. WDM and WDM Computer Networks

Based on the physical technology used, we can identify three generations of networks. First-generation networks consist of those based on copper wire or radio. Networks using fiber in traditional architectures formed part of the second-generation networks. They benefited from fiber’s large bandwidth, low error rate, availability, reliability, and maintainability. However, this improvement was limited by the maximum speed of electronics, because the processing at intermediate nodes was electronic in nature, causing electronic bottlenecks. As mentioned earlier, demand for bandwidth has necessitated newer technologies to quench the bandwidth thirst. The design of all-optical networks forms the basis of third-generation networks. Here, information is conveyed in the optical domain without any intermediate electro-optic conversions. This generation is realized by the emergence of all-optical amplifiers, single-mode fibers, optical couplers, tunable filters (receivers), lasers (transmitters), and all-optical cross-connects [3].

8.2.1. EFFECTIVENESS OF WDM

To distribute the vast bandwidth effectively to multiple users in an all-optical network, one can opt for concurrency. The several ways in
which concurrency can be obtained include through time (OTDM, optical time-division multiplexing), through wave shape (CDM, code-division multiplexing), and through wavelength (WDM) [1, 2].

OTDM employs optical processing to combine many low-speed channels, each transmitted as ultra-short pulses. Using TDM, these channels are combined into a single high-speed channel. This technique avoids the electronic bottleneck and helps to increase the information-carrying capacity of the network to 100 Gb/s or more. However, the transmitters do require the ability to generate ultra-short pulses perfectly synchronized to the desired time slot (channel), and the receivers must be perfectly in sync with the desired time slot (channel).

The concept of code-division multiplexing (CDM) spans the electromagnetic communication spectrum, but differing device capabilities and constraints unique to each spectral domain influence the details of implementation [4]. In this technique, a unique code sequence assigned to each channel is used to encode the low-speed data. These channels are then multiplexed in a single fiber. Because the spectrum of code sequences is much larger than the signal bandwidth, it is possible to have a huge network capacity. However, like OTDM, CDM is constrained by the requirement to generate ultra-short pulses synchronized to the desired channel.

WDM is a relatively recent technology that facilitates significant increases in the data rate that can be carried over a single fiber by the use of multiple wavelengths, each carrying a separate “channel.” WDM achieves this by dividing the optical spectrum into smaller channels, each with a different wavelength, as shown in Figure 8.1. Many users can use such channels simultaneously to transmit and receive data at peak electronic rates, increasing the aggregate network capacity by the number of such channels times the rate of each. Because each user is capable of transmitting data into and receiving data from more than one channel, the transmitters and receivers must be tunable to the different wavelengths in the fiber.

WDM scores over OTDM and CDM in that it does not require complex hardware or synchronization. Although OTDM and CDM are considered long-term network solutions because they rely on immature and different technology, WDM can be realized using commercially available components. However, one of the more important properties of WDM relates to its inherent property of transparency. The fiber channels now act as transparent pipes from end to end and have the freedom to use their desired bitrate, signaling, and framing conventions. Transparency also enables support of
various data formats and a variety of future protocols without much change to the network.

The capabilities of WDM have been greatly influenced by, but not limited to, the following technological advances:

- Distributed lasers and optical amplifiers allow a fiber to have more closely spaced wavelength channels, making 40-channel systems common. Moreover, optical amplifiers enable direct amplification of the optical signal in the optical domain, avoiding the need for electronic circuitry.
- Dense WDM (WDM with large number of wavelengths per fiber), along with TDM, promises up to 80 channels per fiber and 40 Gb/s per channel in the near future.
- Static add/drop multiplexers give the ability to add and drop a subset of wavelengths at intermediate nodes, rather than having to demultiplex the entire set.

Even before the technology could be in place, the applications of WDM had already been developed. Without doubt, such WDM computer networks will find an important place in the future. We will soon be taking an extensive look at current applications that deploy WDM and future trends.
in WDM computer network applications. The next subsection discusses the economic benefits of having WDM in a computer network.

### 8.2.2. ECONOMIC BENEFITS OF WDM

WDM technology has planted its roots in several telecommunication companies, both for point-to-point communication and in metropolitan areas. This is largely because WDM has proved to be more cost-effective than laying new fibers when demand for bandwidth in existing fibers exceeds the required level.

Recent studies have examined the economic benefits of WDM. In [5], the authors analyzed the costs of upgrading the transmission capacity of a point-to-point transmission link from OC-48 to OC-192 using three possible solutions. They considered multifiber, four-channel WDM, and a higher electronic speed (OC-192) solutions. They showed that a four-channel WDM solution had the least cost for distances longer than 50 km. WDM multiplexers (MUX)/demultiplexers (DEMUX) in point-to-point links are now available from several vendors, including IBM, Pirelli, and AT&T [1,6]. Although these products offer a 20-channel solution, the number of channels is expected to increase in the near future.

Another study [7] investigated the economies of WDM and synchronous optical network (SONET) in metropolitan areas under varying cost and demand scenarios. They concluded that WDM proves to be cost-effective in the following cases:

- Metropolitan areas under cable or conduit exhaust scenarios
- Relatively large metropolitan networks, in fiber and regenerator savings (up to 25% savings was found for high-demand areas)
- Architecture using WDM for lower electronic cost by avoiding electrical protection
- Elimination of SONET multiplexers by directly interfacing WDM with the SONET network elements

In access networks, WDM can be used to add flexibility in three key areas:

- **Services:**
  - Multiple types
  - Dedicated and shared services
  - Existing and future services
Topologies:
- Rings, point-to-point, spurs, stars, trees, linear Add/Drop
- Easy handling of unusual rights-of-way
- Seamless integration into existing plant

Capacity:
- Unexpected growth
- Broadband “hot spots”
- Concentration and grooming

A scalable WDM access network architecture based on photonic slot routing, an optical switching approach was proposed in reference 8. They showed that photonic slot routing can be used to achieve statistical multiplexing of the optical bandwidth, thus providing a cost effective solution to today’s increasing bandwidth demand for data transmission.

The economic benefits of WDM to local exchange carrier (LEC) networks under traffic demands projected for the year 2000 formed the basis of another study [9]. The authors employed an aggressive traffic demand model that projected the traffic requirements by a factor of 10 and also assumed SONET as the terminal equipment. Further, they assumed the cost of WDM transmitters and receivers to be negligible. Three metropolitan area networks belonging to various telephone companies were used. They found that the cost savings of using WDM instead of new fiber installations ranged from 16% to 36%, corresponding to a dollar value of $86 million to $151 million.

Clearly, computer networks stand to gain from WDM. With current research and future technological advances, it is anticipated that the next generation of the Internet will employ WDM-based optical backbones. The next few sections highlight some of the computer networks that have already benefited from WDM.

8.3. Local Optical Networks: WDM LAN

This section contains a discussion of local lightwave networks employing WDM. Such networks can be broadly classified into single-hop and multihop networks. The section begins with a description of the architecture
of a local lightwave network employing WDM, then takes a look at the characteristics of single-hop and multihop networks.

8.3.1. **BROADCAST-AND-SELECT (LOCAL) OPTICAL WDM NETWORKS**

As the name indicates, in broadcast-and-select networks each station broadcasts information to all other stations in the network. As described earlier, the optical bandwidth can be divided into smaller-capacity channels, each operating at peak electronic speeds. The transmitters and receivers of such a lightwave network are designed to tune to one or more wavelength channels. Each node (or station) will then be able to transmit and receive data corresponding to the band of wavelength channels to which it can tune. The broadcast requirement necessitates that each end node be able to make connections with any other end node. Efficient network operation would therefore depend on the following:

- The ability of the transmitters to avoid interchannel interference by having a narrow line width
- The ability of the receivers to filter each channel individually, which would require narrow bandwidth filters
- The ability of the tunable components to cover all channels

The types of connections that can be set up depend on the tunability of the transmitters and receivers. Currently, four types of organization are available, based on the tunability in the network and assuming one transmitter/receiver per node:

- Fixed transmitter/fixed receiver
- Fixed transmitter/tunable receiver
- Tunable transmitter/fixed receiver
- Tunable receiver/tunable receiver

8.3.1.1. **Physical Topologies for a WDM LAN**

A possible configuration of a broadcast-and-select network is shown in Figure 8.2. It consists of an $N \times N$ star coupler (a star coupler is a device that combines light into or splits light out of the fiber), followed by a $1 \times N$ splitter (a splitter is a coupler that divides an optical signal from one fiber into two or more fibers). By this arrangement, the input signal from any
A station can be divided equally among all of the $N$ outputs with a power of $P_{\text{out}} = \frac{P_{\text{in}}}{N}$. The advantages of the broadcast star are its logarithmic splitting loss in the coupler and the absence of tapping or insertion loss and electro-optic conversion. Moreover, the passive nature helps to improve network reliability because the coupler does not require power to operate.

The broadcast nature makes this a simple architecture to implement, but such networks suffer from the following drawbacks:

- **Wavelength reuse**: The broadcast-and-select approach necessitates a large number of wavelengths, at least equal to the number of nodes in the network. In practice, even more wavelengths may be needed. This is basically due to the lack of wavelength reuse in the network.
- **Splitting loss**: Each node receives only a fraction of the transmitted power, and this fraction becomes smaller with an increase in the number of nodes. The resulting power loss due to splitting would necessitate optical amplifiers beyond a certain point.
- **Scalability**: Lack of wavelength reuse prevents this architecture from being implemented in WANs.

Compared to a centralized, nonblocking, space-division switch that does not have WDM (the aggregate system capacity is still the same as that of the
The passive star WDM solution is superior in the following aspects:

- The passive star can survive if one node goes down, due to the distributed nature. Hence it can provide better fault tolerance than the centralized approach, in which the entire system would go down if a node failed.
- The centralized coordination for multicasting support requires more processing than the passive-star approach, which allows multicasting for free.
- Passive star is potentially cheaper than its counterpart because very little electronics are involved.

The alternatives to a star topology are the bus and the tree. Bus and tree topologies for a local lightwave network with WDM are shown in Figure 8.3.

In a bus topology, the end-nodes use combiners and splitters to transmit into and receive from the bus, respectively, as shown in Figure 8.3a. In a tree topology, a unique wavelength is assigned to each node, to which its laser is tuned. A tunable receiver capable of tuning into all available wavelengths is also present. Here, too, combiners and receivers are used to transmit into and receive from the tree, respectively. The star topology is capable of supporting a larger number of users than the linear-bus topology, due to the absence of power and tapping loss. However, developments in the amplifier arena, especially the erbium-doped fiber amplifier (EDFA) has rekindled interest in the tree topology, which is now being examined for deployment in MANs.

![Bus Topology](a) Bus Toplogy ![Ring Topology](b) Ring Topology

**Fig. 8.3** Broadcast topologies.
8.3.1.2. Single-Hop and Multihop Networks

The tunability of transmitters and receivers gives rise to a magnitude of networking possibilities. The choice of network architecture allows the tunable transceivers to be used in a single-hop or a multihop configuration.

As the name suggests, single-hop networks involve transporting the information from a node, in optical form, directly to the destination without intermediate conversion to electronic form. Obviously, because signal is in optical form throughout its journey, high speeds are obtainable. However, nodes in the network must have a significant amount of dynamic coordination. A packet transmission requires the transmitter of the sending node and the receiver of the receiving node to tune to the same wavelength channel throughout the duration of the transmission.

The transceivers must be able to tune to different channels quickly enough to enable packet transmission in quick succession. Current tuning times are large compared to packet transmission times, and the number of channels they can tune to is small. The challenge here is to develop efficient protocols that help in data coordination. The bandwidth allocation among the participating nodes must be managed efficiently. Based on the type of coordination provided, two techniques are possible: those that use pretransmission coordination and those that do not use any pretransmission coordination.

In systems that use pretransmission coordination, the transmission requirements of the nodes are taken care of by one or more control channels, and the actual data is transmitted through data channels. The control channels may be monitored by the idle nodes. Nodes tune to the appropriate channel before data packet transmission or reception. When there is no pretransmission coordination, the arbitration between contending nodes is done in a predetermined manner, and there is no control channel present. Contention-based mechanisms could also be used for this purpose. However, such deterministic scheduling may not be very useful when the number of users is large and varies with time. Hence, dynamic pretransmission coordination tends to be preferred in such cases.

In multihop networks, nodes transmit data to other nodes through one or more hops. Hops here refer to transmitting data through other nodes. Hence, nodes in a multihop network also act as intermediate routing nodes. Intermediate routing nodes perform the function of transmitting the signal to the next hop (node) until the final destination is reached. Key properties of such networks include the relative independence of the physical topology of the network (the fiber layout) and the logical interconnection
pattern among nodes. The transceivers of each node are tuned to a particular channel and are usually not expected to change unless a global reassignment is done. Because it is unlikely that nodes communicate in a single hop, various virtual structures play an important role in determining operational features and performance characteristics.

Transceiver tuning times do not affect the performance of multihop networks, as they do in the single-hop case due to its static nature. However, there are some other issues that must be handled effectively in multihop networks. First, the average hop length (the number of hops between the source and destination node) and the average packet delay should be as small as possible. Second, the processing involved at the nodes should be simple to avoid delays. Both these constraints reflect on the virtual structure chosen. An interesting issue in such networks relates to the nature of the wavelength channel used: whether channels are dedicated or shared in nature. Although dedicated channels allot a wavelength channel for each virtual link, shared channels allow wavelengths to be shared by virtual links. Shared channels allow increased utilization of channels, but they also require mechanisms to arbitrate the sharing of channels among the contending nodes.

The next section takes a look at the architectures employing WDM at the metropolitan level.

8.4. Metropolitan Optical Networks: WDM MAN

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 long-haul transoceanic and terrestrial networks [10]. Commercial availability in the long-haul market has triggered the use of WDM in metropolitan areas and eventually in access networks. This section discusses the metropolitan architectures that use WDM. It begins with a brief survey of the technologies that are viable in the metropolitan market, followed by a description of the role of WDM in MANs.

8.4.1. METROPOLITAN TECHNOLOGIES

Many technologies have been considered for metropolitan-area networks. The key requirement of these networks relates to the support for varying traffic types, both old and new.
- **SONET/SDH**: One of the founding technologies used in MANs, this TDM-based approach has been used for both TDM-based circuit switched networks and most overlay networks. SONET allows midspan meet and multivendor compatibility. That is, it allows network providers to communicate irrespective of the equipment vendor, and midspan meet allows network providers and their customers to share the SONET infrastructure optimally. However, cost, scalability, and unresponsiveness to bursty IP traffic limit this technology.

- **ATM**: ATM has revolutionized telecommunications, becoming an integral part of the networking infrastructure. ATM provides a common transmission format for all protocols and traffic types for transmission over a SONET infrastructure. Although IP over SONET (POS) is preferred, ATM still has a strong hold on the metropolitan front. Its major advantages include high-speed line interfaces, efficient virtual circuit services, and traffic management. ATM also accommodates bursty data, voice, and video, making it the preferred choice for such applications.

- **Gigabit Ethernet**: From its origin 25 years ago, Ethernet technology has evolved to meet the increasing demands of packet-switched networks [11]. The advent of Gigabit Ethernet has facilitated migration to a proven, reliable, and uncomplicated technology. Ten Gigabit Ethernet, in particular, provides an efficient and effective solution for high-speed networks. Besides being less expensive, it provides the ability to support new applications and datatypes, and flexibility in network design. Moreover, it allows multiple vendor sourcing and provides interoperability.

There is good competition among the aforementioned technologies for implementation over an optical network. The question remains as to which one will ultimately succeed. Figure 8.4 shows the data link and network protocols over the optical layer.

### 8.4.2. WDM IN METROPOLITAN AREA NETWORKS

The demand for bandwidth created by new applications, such as e-commerce, packetized voice, and streaming multimedia, has created a bottleneck in the MAN. To some extent, WDM technology has helped to satisfy these demands. There are two important applications of WDM to such networks: in SONET migration and in storage area networks (SANs).
8.4.2.1. Storage Area Networking and WDM

Applications involving e-commerce, databases, and online transaction processing eat up considerable storage space to the extent that they not only need more space but also require efficient storage management. SANs are a direct consequence of this requirement. They essentially start out as a group of server systems and storage devices interconnected by fiber channel adaptors to a network. Scalability is obtained by adding new hubs that allow fiber channel switches to be incorporated.

A typical SAN architecture is shown in Figure 8.5. It consists of servers, storage devices, and network devices (multiplexers, routers, switches, etc.). In fact, it forms an entire network in itself, away from the LAN. The major applications provided by a SAN are transaction processing, data mirroring, and backup and restoration. The data link technology commonly used in SAN is the fibre channel. Fibre channels provide interfaces at 100 MB/s today. The fibre channel supports several configurations, including point-to-point and switched topologies [12]. The fibre channel arbitrated loop (FCAL) used in SAN facilitates a high-speed storage network by its inherent virtue to provide any-to-any connectivity among servers and storage devices. Apart from providing high-speed interconnection between storage devices.
devices, FCAL also delivers reliability. The fibre channel plays a vital role in the success of the SANs.

One typical interface to a SAN is the IBM’s Enterprise System Connection (ESCON), a 17 MB/s half-duplex protocol over fiber. The major disadvantage of such fibre channel-based technologies is the maximum distance obtainable. Increase in distance affects performance beyond the distance limits. It is here that WDM proves to be advantageous. The limitation in distance can be overcome by interfacing one or more SANs over the optical layer using WDM. Not only can the distance limit be improved greatly, but the performance is also improved. Access to the ring is by way of “satellite” OADMs with fibre channel or ESCON interfaces at each SAN location [10]. Significant savings can also be obtained by multiplexing the fibers used in the fibre channel over a WDM transport, thus reducing the fiber requirements. The architecture of such a network is shown in Figure 8.6.

8.4.2.2. SONET and WDM

As mentioned earlier, SONET, though a reliable mechanism in providing interoperability, protection, and network management, lacks in scalability.
Upgrading SONET is an expensive task due to the cost of additional equipment (line-rate-specific network elements) that is required to handle traffic. DWDM offers a solution to this problem. Using DWDM, fiber capacity can be increased greatly, while SONET infrastructure can be preserved. Thus, we can have SONET networks on top of WDM. Put technically, the physical layer of SONET will be replaced by WDM. The International Telecommunications Union (ITU) has come up with the definition of a new layer called the **optical layer** for such purposes. The optical layer provides a *lightpath*, an all-optical path from source to destination, and uses a wavelength on each link between the source and destination. The optical layer facilitates the removal of SONET add/drop multiplexers (ADM) and their replacement with DWDM equipment. This allows the routers and other devices to have a direct interface to DWDM by bypassing SONET equipment. The migration is schematically shown in Figure 8.7.

Figure 8.7a shows the state of SONET before migration. Here, the interface to the network is through SONET ADMs. Figure 8.7b shows the use of DWDM to increase the capacity of the existing ring, and Figure 8.7c shows how DWDM can be used to replace ADMs. The next section discusses the use of WDM in WANs.
8.5. Wide Area Optical Networks: WDM WAN

This section takes a look at the role of WDM in wide area networks, also known as wavelength routing networks. We begin with a brief introduction to wavelength routing networks and then look at the various components and technologies involved in such networks.

8.5.1. WAVELENGTH ROUTING NETWORKS

Before the onset of wavelength routing networks, broadcast-and-select networks were the prevalently studied technique. But lack of wavelength reuse and splitting losses prevented this architecture from being implemented in WANs. Wavelength routing networks offer an alternative solution to these drawbacks. These networks rely on optical devices, such as grating multiplexers and demultiplexers, that perform wavelength-sensitive routing. Wavelength reuse forms an integral part of such networks, and wavelengths can be reused as long as no two sessions that share the same link use the same wavelength at the same time. This is illustrated in Figure 8.8.
Wavelength routing networks consist of one or more *wavelength routers*, which are wavelength-selective elements made of glass, interconnected by fiber links. They route the optical signal at the input ports to the corresponding output ports based on the wavelength on which they arrive. The figure shows three sessions: two on wavelength $\lambda_1$ and one on wavelength $\lambda_2$. At any time, each node (wavelength router) can have several logical connections with several other nodes. As long as the paths taken by any two connections do not overlap, they can be set up on the same wavelength. This causes a tremendous reduction in the number of wavelengths required.

### 8.5.2. FIXED AND CONFIGURABLE WAVELENGTH ROUTERS

Wavelength routing networks can be classified as *fixed* or *configurable*, based on the capability of the network devices. The routing node architectures for a passive and a configurable routing network are shown in Figures 8.9 and 8.10, respectively.

In a fixed or passive network, the input port and the wavelength on which the signal is transmitted determine the path. The signals are then routed by
Thus, fixed networks require tunable transceivers. The tuning requirements on transceivers and the number of wavelengths necessary for a given connectivity can be reduced by making the routing node dynamically reconfigurable [13, 14]. This is made possible through photonic switches that are provided for each wavelength.

On the other hand, reconfigurable routers can switch or route each signal independently of the other signals on different wavelengths on the same port by employing photonic switches. As shown in Figure 8.10, the input signals are first demultiplexed and then are grouped according to the wavelengths on which they arrive. Signals from each group (signals with the same wavelength) are sent to individual switches. The switch then routes the signal to the appropriate output port, where the signals are multiplexed and sent out. The most important property of such routers relates to the flexibility in adapting to changing traffic demands by dynamically establishing or terminating lightpaths between the network’s end nodes.
8.5.3. WAVELENGTH CONVERSION

In simple wavelength routing networks, to be successfully established a lightpath between two nodes must be assigned a single wavelength on all the links of the path. This constraint, referred to as the wavelength continuity constraint, limits flexibility in using available wavelengths and requires careful wavelength assignment in order to keep the number of blocked wavelengths to a minimum. Wavelength reuse can be improved by overcoming the wavelength continuity constraint.

Consider the network shown in Figure 8.11 and assume that two lightpaths—(1,4) using $\lambda_1$ and (2,3) using $\lambda_2$—are established. Suppose that a new lightpath (1,3) needs to be established. The wavelength continuity constraint would prohibit this path from reusing any of the two wavelengths and would necessitate a third wavelength. In such a case, if we could convert wavelengths at node 2, session (1,3) could be assigned $\lambda_1$ on link between 1 and 2 and $\lambda_2$ on link between 2 and 3. Wavelength conversion
could play a significant role in improving the utilization of the available wavelengths in the network or, alternatively, reducing the blocking rate for lightpath requests. Devices that perform such wavelength conversion are termed *wavelength converters*. In the preceding example, a wavelength converter would be placed at node 2.

The conversion capability of a node may be characterized by the conversion degree $d$, where $d$ varies from 1 through $F$, $F$ representing the number of wavelengths in a link. The most flexible situation corresponds to a node having *full wavelength conversion*, where any wavelength can be converted to any other wavelength and hence $d = F$. On the other hand, $d = 1$ corresponds to the node having *fixed wavelength conversion*, in which the input/output wavelength mapping is fixed; that is, an incoming wavelength is always converted to a fixed outgoing wavelength [15]. *No wavelength conversion* is a special case of fixed conversion in which the incoming and outgoing wavelengths are the same, and *limited conversion* is a limiting case of full wavelength conversion in which a signal entering a node on a certain wavelength may leave the node on any wavelength $\lambda$ in $S(\lambda_i)$, where $S(\lambda_i)$ is the subset of wavelengths to which it can be converted. Finally, *sparse wavelength conversion* refers to the case
in which full wavelength conversion is available at a subset of network nodes.

Converters are placed at the switches in the network and are likely to remain expensive, so one would like to use them minimally. This gives rise to the problem of placing the converters optimally in the network. Numerous algorithms have been proposed in this regard. The main goal of these algorithms is to place the given set of converters in such a way as to obtain the least blocking probability. The usefulness of converters depends on a variety of parameters, including the topology of the network, the traffic demand, and the number of wavelengths, among other factors [16].

8.5.4. ROUTING AND WAVELENGTH ASSIGNMENT

In order to take full advantage of the wavelength routing technique, quite a few design problems must be handled effectively. One such problem relates to the setting up of lightpaths that minimize the number of wavelengths required. A practical situation in such a case would be the following. Given a network topology and a set of end-to-end lightpath requests, determine a route and wavelength(s) for the requests using the minimum possible number of wavelengths [15]. This is referred to as the routing and wavelength assignment problem, where routing refers to the selection of routes for the lightpath requests and wavelength assignment refers to the assignment of wavelengths for the lightpath. The given topology includes the cross-connects and the location of wavelength converters (if any) in the network.

It is difficult to predict the bandwidth requirements and the statistical properties of the traffic that will be carried by future wavelength routing WDM networks, but consideration of these factors is important for network design and analysis. These bandwidth requirements, in a sense, determine the extent to which the lightpaths are dynamically established due to time-varying fluctuations in traffic demand [17]. Depending on the rate at which the traffic varies, the lightpaths can either be established on a static basis (without much variation) or assigned dynamically (with lightpaths entering and leaving the network on a demand basis). A realistic network could have some lightpaths that are established on a static basis and others that are established and torn down as new calls arrive and depart.

WDM networks with dynamic lightpaths perform routing in two ways. In offline routing, all the lightpaths that need to be established are known in advance, and the task is to find the route and assign wavelengths to
them such that an objective function (typically, the number of wavelengths per link) is optimized. Under this method, if a new lightpath is to be added to the existing set, it may be necessary to rearrange all the existing lightpaths and reassign new wavelengths to them. But rearranging existing lightpaths every time a new call arrives may pose a practical problem. On the other hand, online routing involves establishing new lightpaths without affecting the existing lightpaths.

Wavelength routing is the most popular and effective technique for WDM networks, and routing and wavelength assignment (RWA) forms an integral part of network design. Along with wavelength conversion, the RWA algorithm used plays a dominant role in determining the blocking performance of such networks. The next section takes a look at some recent applications of WDM to computer networks.

8.6. WDM Technologies on the Horizon

This section presents a discussion of recent applications that have been used experimentally with WDM. A description of various emerging technologies in WDM optical networking can be found in reference 20.

8.6.1. PASSIVE OPTICAL NETWORKS

The development in optical networking technology has always pointed toward having an all-optical approach so as to avoid the transition to electrical signals. Devices such as optical switches, cross-connects, and optical amplifiers have been triggered by the aforementioned goal. One such device is the optical splitter, which splits the given signal into two or more signals in the optical domain. Optical splitters are small and do not need any additional housing. Passive optical networks (PONs) were developed with such properties in mind.

The general architecture of a PON is shown in Figure 8.12. Through an optical line termination (OLT) unit, the local exchange connects to the network. The OLT is capable of either generating optical signals on its own or passing the optical signals from optical cross-connects. The signal from the OLT is split using passive splitters and given to optical network units (ONUs). The ONU can be used in a fiber-to-the-premises (FTTP) case as an interface to the copper fiber, or in a fiber-to-the-curb (FTTC) case.
as a termination to allow the balance of the local loop to be provisioned over copper. It can also be used in the fiber-to-the-neighborhood (FTTN) scenario as a termination agent. Finally, through an optical network termination (ONT) unit, service is provided to homes. The termination unit has interfaces with the backbone network, which aids in providing the service to users.

The required connections can be achieved through multiplexing techniques. **ATM-based PON** (APON) has already been standardized by the ITU-T. Another attractive standard is the **Ethernet-based PON** (EPON), which is in the process of being finalized. It offers great potential for PON, due to its support for Gigabit Ethernet and 10 Gigabit Ethernet. Finally, WDM technology, with its frequency splitters, could be in line for standardization. WDM provides an attractive solution on the first mile because of its technology and the fact that it does not involve any signal division. Moreover, WDM systems can allow individual users to use their own wavelength channel at its full speed. Arrayed waveguide gratings or dielectric filters can be used as frequency splitters. However, **WDM-based PON** (WPON) is still in its infancy, due to the following bottlenecks that must be overcome:

- The equipment that is to be kept at homes is complex, and replacing it would require a supply of ONTs to all possible frequencies.
If two homes used the same wavelength for transmitting, there could be interference in the passive splitter. Solutions have been proposed in this direction, including using tunable lasers, using optical connecting cables for the ONT to determine the laser frequency, and replacing the laser in the ONT with a modulating mirror. WPONs still remain in the research stage, although this technology has the potential to give PONs an enhanced performance level.

8.6.2. IP OVER WDM

The rapid growth of the Internet and the increasing demand for bandwidth require an efficient protocol stack for transmission and reliable bandwidth provision over the links. IP, as we all know, has become the standard protocol for all Internet applications and is expected to be the dominant standard for the backbone in coming years. Optical technology, on the other hand, has immense potential to quench the bandwidth thirst of future applications. Recent developments in WDM technology promise to increase the traffic capacity of optical networks. This makes it important for these two technologies to coexist by taking advantage of each other.

Internet growth not only requires providing immense bandwidth but also triggers the need for providing guarantees with respect to quality of service, security, and fault tolerance. Currently, telecommunication networks use SONET for transmission, multiplexing, and protection, and SONET is implemented over WDM lightpaths (IP over SONET over WDM). An alternative approach could implement IP directly over WDM, bypassing the SONET layer. Here, only the SONET framing is maintained; the rest of the work is transferred to WDM. This approach of interfacing IP directly with WDM would give the following advantages, among many others to come:

- Overall reduction of equipment costs and management complexity
- Improved bandwidth efficiency

The issues that must be addressed in such a network relate to the effective interoperation of IP and WDM. This could involve changes in either layer to take advantage of the other. For example, the IP layer could handle the information pertaining to traffic type and QoS requirements, and WDM would then establish on-demand lightpaths for the different IP flows and provide differentiated services for different classes of traffic.
8.6.3. **WDM-BASED PHOTONIC SWITCHES**

As we have seen, WDM networks are being chosen to circumvent the electro-optic speed mismatch by partitioning traffic. All-optical transmission eliminates the need for every node in the network to receive and process all network traffic. WDM networks are established using tunable transmitters and/or receivers to switch between the multiple channels created on the single optical fiber.

Photonic networks are faced with a major obstacle, which relates to the speed mismatch between the high-speed optical components and the interface electronics [18]. This is especially true when it comes to a packet-switched network. WDM networks could be an alternative to the photonic switches currently used.

Authors in [18] built such a WDM testbed, called “lightning.” This architecture was designed to provide a consistent and scalable technique that would give a high-performance clustering of geographically distributed processors. It aimed at two main classes of interconnection: supercomputer-class system interconnection and high-end workstation-class processor interconnection. Moreover, it achieved single-hop optical communication, meaning that the packets remain in optical form between end nodes and do not require intermediate routing. The WMD hierarchical structure provided wavelength reuse at all levels, thus enabling the system to scale to very large sizes. Another significant advantage of this architecture is its ability to vary dynamically the bandwidth provided to the various levels in the hierarchy and its capability to reallocate bandwidth in a decentralized manner, allowing any node to initiate it. This provides fault-tolerant behavior. More details on the architecture can be found in [18].

8.6.4. **MILITARY APPLICATIONS**

Numerous applications have been identified in military systems that stand to benefit from WDM. It has been predicted that multiple programs will benefit from WDM development. As we have seen, Ethernet along with WDM is prominent in MAN and LAN topologies. Because military platform networking most resembles the MAN environment, with a high priority on quality of service, WDM would be a natural choice for such applications. The customers in such areas require applications ranging from high-speed ATM to SAN, LAN, and resource sharing. The military can leverage on commercial WDM investments to satisfy their future
bandwidth requirements and for miscellaneous Navy/DOD requirements and applications.

A few areas of military interest in WDM include network ruggedization (strengthening the network to resist wear or abuse), mixed signal antenna networking, optical signal processing, and optical domain microwave filtering. The future military optical networking vision could include high-capacity, mixed-signal WDM fiber-optic networks that satisfy military platform requirements.

Current technological advances in WDM permit such networks to allow both analog and digital signaling and to provide sensor and network information in real time. Moreover, WDM provides increased flexibility and reduced installation and servicing time. However, some challenges still remain in getting an improved analog WDM fiber-optic link performance and in the integration and packaging of WDM link components. In the case of optical domain microwave filtering, WDM eliminates the need for an electronic mixer and helps the system filter build on commercial DWDM telecommunications and millimeter-wave fiber-radio system technologies. WDM-based signal processors are also available with fast tunable lasers and broadband optical sources. The main challenge in this area, as mentioned, relates to obtaining low cost, size, weight, and power with advanced fabrication, integration, and packaging.

In the naval arena, the following applications of WDM have been identified:

- Unified networks for aircraft/unmanned contact air vehicles (UCAV) avionics and vehicle management system (VMS)
- Free space interconnects
- WDM computer backplanes/interconnects
- Smart skins/structures interconnect and diagnostics
- Missile and decoy interfaces
- True time delay/A/D conversion

Current developments in WDM in this direction include the Focus program, which is building a WDM digital/RF network for the advanced electronic attack (AEA) platform, the SBIR phase II WDM RF network, broadband WDM component developments, and a P-3 “hairy buffalo” demonstration, which is a sensor integration platform being developed using WDM networks.

Despite significant commercial and DARPA funding of WDM technology, WDM has yet to impact naval aerospace platforms. Affordability,
environmental compatibility, and the technology readiness level remain impediments [19]. Here again, component packaging technology needs to mature.

8.7. Summary

With bandwidth needs for the Internet doubling each year, companies are faced with problems in trying to tackle the demand. Optical WDM networking technology offers an effective solution to these problems, due to its inherent capabilities and advantages. More and more companies are trying to incorporate WDM in their applications. This chapter has summarized the various computer networking applications that stand to gain from deploying WDM. In particular, it presented the architecture of local, metropolitan, and wide area networks that use WDM. The advantages of such architectures, compared to the alternatives, were highlighted. The chapter also discussed recent trends in WDM usage in various fields and the need for improvement in the current technology to make WDM usable in such fields. Given the rate at which optical technology is maturing, there is no doubt that WDM will be a favorite and widely deployed technology in the near future.

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