An Overview of DWDM Networks

by Shaowen Song

Wilfrid Laurier University, Waterloo, ON

Abstract

This article provides an overview of the applications of Dense Wavelength Division Multiplexing (DWDM) technology. It examines the network architecture and the recent development of two major DWDM-based networks, namely the backbone network and the residential access network. The DWDM applications in Local Area Networks (LANs) are not included in the article. The article also looks into the future of broadband integrated service networks based on the DWDM technology.

Sommaire

Cet article présente un survol des applications de la technologie du “Dense Wavelength Division Multiplexing” (DWDM). On y examine l'architecture et les développements récents de deux réseaux basés sur le DWDM: le réseau central DWDM et le réseau d'accès résidentiel DWDM. Les applications DWDM dans les réseaux locaux (LANs) ne font pas l'objet de cet article. Cet article présente aussi un aperçu de l'avenir des réseaux de services intégrés à large bande basés sur la technologie DWDM.

1.0 Introduction

In traditional optical fiber networks, information is transmitted through optical fiber by a single lightbeam. In a wavelength division multiplexing (WDM) network, the vast optical bandwidth of a fiber (approximately 30 THz corresponding to the low-loss region in a single-mode optical fiber) is carved up into wavelength channels, each of which carries a data stream individually. The multiple channels of information (each having a different carrier wavelength) are transmitted simultaneously over a single fiber. The reason why this can be done is that optical beams with different wavelengths propagate without interfering with one another. When the number of wavelength channels is above 20 in a WDM system, it is generally referred to as Dense WDM or DWDM. We use DWDM as a general term in this article.

DWDM technology can be applied to different areas in the telecommunication networks, which includes the backbone networks, the residential access networks, and also the Local Area Networks (LANs). Among these three areas, developments in the DWDM-based backbone network are leading the way, followed by the DWDM-based LANs. The development on DWDM-based residential access networks seems to be lagging behind at the current time. This article provides an overview of the network architectures that have been developed for the backbone networks and the residential access networks. This article also examines the current status and the potential future of these two types of networks. DWDM application in LANs is considered as a separate area, which is not included in this article.

2.0 DWDM Backbone Networks

2.1 Overview

We can divide the network structures of DWDM-based backbone networks into three classes:

- Simple point-point DWDM link,
- DWDM wavelength routing with electronic TDM (time domain multiplexing) and switching/routing backbone network, and
- All-optical DWDM network.

This section discusses the network architecture and the mechanisms of these three types of DWDM backbone networks.

2.2 Point-To-Point DWDM links

The simplest application of the DWDM technology in backbone networks is the point-to-point link. Figure 1 shows the architecture of the networks using 4 network switching/routing nodes as an example. In this architecture, the electronic nodes can be SONET/SDH switches, Internet routers, ATM switches, or any other type network nodes. The DWDM node consists of typically a pair of wavelength multiplexer / demultiplexer (lightwave grating devices) and a pair of optical-electrical/electrical-optical convertors. Each wavelength channel is used to transmit one stream of data individually. The DWDM wavelength multiplexer combines all of the lightwave channels into one light beam and pumps it into one single fiber. The combined light of multiple wavelengths is separated by the demultiplexer at the receiving end. The signals carried by each wavelength channel are then converted back to the electrical domain through the O/E convertors (photodetectors). In this way, one wavelength channel can be equivalent to a traditional fiber in which one lightbeam is used to carry information. The dotted-lines in Figure 1 represent the wavelength channels. It is worth noting that the wavelength channels in one fiber can be used for both directions or two fibers are used with each for one direction.

The advantage of the point-to-point DWDM links is that it increases the bandwidth by creating multiple channels with low costs. The limitation of this approach, however, is that the bandwidth of each wavelength channel may not be fully utilized due to the speed of the electrical devices, which is referred to as the well-known electro-optic bottleneck. Also, the use of the wavelength channels may not be optimal due to the fact that the meshes formed by the wavelength channel are all identical, which can be seen in Figure 1.

2.3 Wavelength routing with electronic TDM

Figure 2 depicts the second type of DWDM application in backbone networks, in which wavelength routers are used to configure or reconfigure the network topology within the optical domain and the TDM (Time Domain Multiplexing) network nodes are used to perform multiplexing and switching in the electrical domain. This combined optical and electrical network architecture can be applied in SONET/SDH in which the electrical TDM network nodes would be SONET switches, or

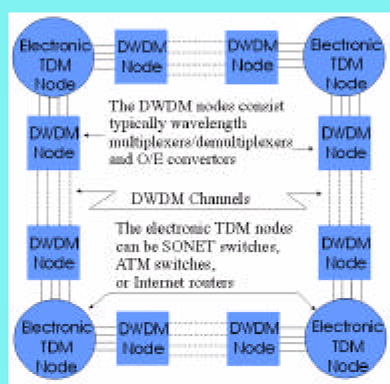


Figure 1: DWDM point-to-point link backbone network

Figure 2: Wavelength routing with electronic TDM DWDM networks

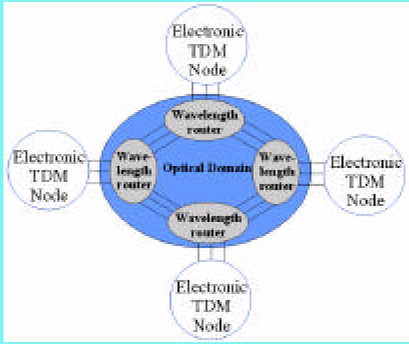
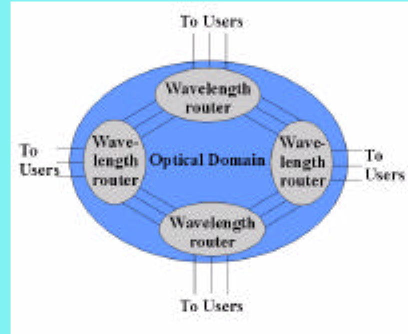


Figure 3: Wavelength switching without TDM



in the Internet in which the electrical TDM network nodes would be the Internet routers. The architecture can also be used in an ATM network where the electrical TDM network nodes would be ATM switches.

The advantage of this combined architecture in comparison with the simple DWDM point-to-point links is that it can optimize the use of DWDM wavelength channels by reconfiguring the mesh formed by the wavelength channels. The topology of reconfiguration can be dynamic in which network topology is reset periodically according to the traffic with the time period in the order of seconds or milliseconds. The reconfiguration can also be static in which the mesh is set for a longer period of time. The enabling technology for this architecture is the wavelength router in the optical domain. Different types of wavelength routers are available commercially which range from mechanically controlled to thermally controlled and to semiconductor wavelength switches.

The advantage of this architecture is its ability to utilize the bandwidth capacity to the level that the electronics can handle, because of the reconfiguration of the mesh by the wavelength routers. The problem, however, is still the electro-optic bottleneck. Nevertheless, it has improved in comparison with the point-to-point DWDM links.

Several technical issues are required to be dealt with for this architecture, which include the control system for the mesh reconfiguration, the traffic evaluation among the DWDM channels and among the fibers, as well as the technology for constructing the wavelength routers. These technical issues have been the topics of research for some time and all are still undergoing development at the current time.

2.4 All-Optical DWDM Networks

The goal of all-optical DWDM networks is to eliminate the conversions between electricity and light. The all-optical network is also referred to as the transparent network. Two types of all-optical DWDM backbone networks have been proposed, which are:

- Wavelength switching DWDM networks without TDM [1], and
- DWDM with optical domain TDM [2].

These two types of DWDM backbone networks are discussed in the following two subsections.

2.4.1 Wavelength switching without TDM

Circuit switching can be achieved by using wavelength switches (also called wavelength routers). Figure 3 shows the architecture of the network, in which wavelength switches are used to establish connections between the two communicators. This is quite the same as the old PSTN (Public Switched Telephone Network) system where the crossbar type of electrical switches are used to establish the circuit for the two users.

The wavelength switches for this type of networks can switch among the wavelength channels of multiple fiber input and output ports. A wavelength router may have the additional capacity of changing the wavelength of the signal between routers resulting in high utilization of wavelength channels. In the case of a wavelength router without wavelength conversion, the two users involved in the communication are connected by one signal wavelength across all of switches in the light path. However, with the wavelength conversions, the two sides of the communication can be connected by different wavelengths in different fiber links between switches. Figure 4 shows an example of a wavelength router structure with multiple fiber inputs and outputs.

The advantage of this type of DWDM network is its simplicity in the switching mechanism. The major problem for this network is the under utilization of the bandwidth capacity of the wavelength channels. This is because once the light path is established between the two sides of the communication parties, it is up to the user to use the available bandwidth of the wavelength channel which can be tens of GHz or even hundreds of GHz. It is obviously inefficient for voice communications. Therefore, this type of all-optical DWDM backbone networks will unlikely be used to replace the SONET/SDH. However, it can be useful for Enterprise intranets where different types of communications can share the same network with low costs of building it. Also, because of the transparency of the network, it provides many advantages, such low error rate and low maintenance costs.

2.4.2 Wavelength switching with optical TDM

As it has been mentioned above, the wavelength routing all-optical network has the problem of low efficiency in utilizing the bandwidth of wavelength channels with each having the capacity of hundreds of Gigabits per second. Although the combined wavelength routing and electronic time domain multiplexing can increase the bandwidth utilization to some degree, it introduces the O/E conversions that may restrict the speed and cause packet delays. Therefore, it is natural to implement optical TDM in future optical networks, which eliminates the O/E conversions resulting in a transparent high-speed all-optical network.

Replacing the electrical TDM nodes in the DWDM with electrical TDM architecture (Figure 2) by optical TDM nodes, we obtain a DWDM wavelength routing with optical TDM architecture, as shown in Figure 5. As we have mentioned in Section 2.2 that the electrical TDM/switching nodes in Figure 5 can be of any kind, such as SONET/SDH switches, Internet routers, and ATM switches. This indicates that the all-optical TDM nodes in the all-optical architecture can be optical SONET/SDH switches, or all-optical ATM switches, or all-optical Internet routers. Different types of all-optical TDM/switch nodes can also be in one network, provided the protocol conversions are implemented.

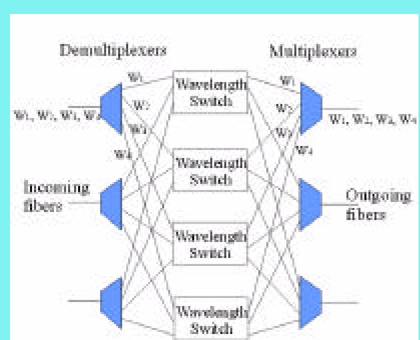


Figure 4: A wavelength router

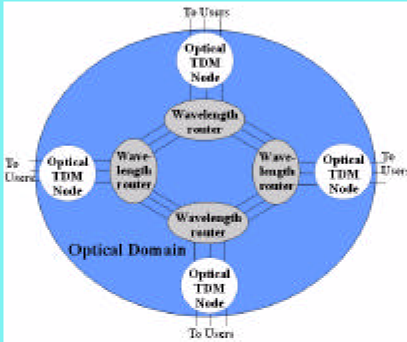


Figure 5: All-optical TDM/switch with wavelength router

In fact, the optical TDM/switch node and the wavelength router in one routing site (Figure 5) can be combined into one all-optical switching node that not only forwards packets through time domain multiplexing but also selects the light path intelligently according to the availability and traffic loads of the links. This architecture is shown in Figure 6.

The only question left so far is how can we build such all-optical TDM/switch nodes. This is the problem that has not been solved. Although some research and proposals have been published, such as using a hybrid mechanism where electrical signals are used to perform the control and light signals are used to carry the data [3], the system is far from mature. Also it still involves electricity which still has many problems to be dealt with.

Looking into the possibilities of building the three major types of the current electrical switches, namely the SONET/SDH switch, the ATM switch, and the Internet router, the SONET/SDH switch is the simplest one among the three since it is for circuit switching. The Internet router is the most complex one among the three, since it requires a digital optical processor and all-optical memories. In any case, digital optical logic devices are required to build these switches. Therefore, it seems clear that we need to have optical digital processing power before we can implement any of these TDM switches, unless other mechanism emerges to revolutionize the existing concept of packet switching networks.

3.0 DWDM Access Optical Networks

3.1 Overview

An overriding belief existed even in the early 1970's that optical fiber would one day make its way into the subscriber loop and be used to connect individual homes. Research on the fiber based residential access network architecture and protocols have since then become one of the major areas in the telecommunication arena. The ATM (Asynchronous Transfer Mode) based B-ISDN (Broadband Integrated Services Digital Network) architecture had been once believed to be the leading candidate for realizing the fiber-to-the-home access network. However, with the technological development of the DWDM, broadband residential access fiber network has taken another turn, which leads to a DWDM-based fiber optical network to deliver both narrowband and broadband services. This section provides an overview of the network architectures that have been developed for the residential access networks based on the DWDM technology.

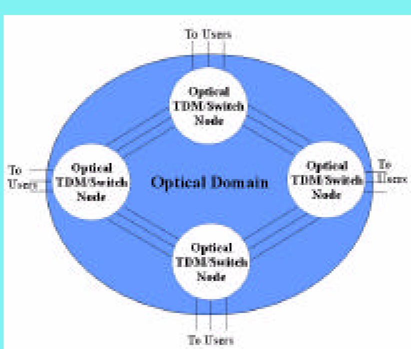


Figure 6: All-optical TDM/switch with self wavelength selection

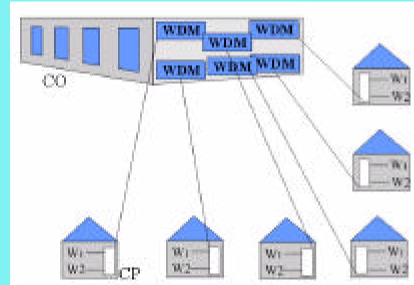


Figure 7: Single-star PON architecture

DWDM-based access optical networks can be classified into two categories, passive DWDM access networks and active DWDM networks. The term of active DWDM network here refers as to the DWDM network in which the TDM (time domain multiplexing) is applied in the wavelength channels. These two types of access network architecture are discussed in the following subsections.

3.2 DWDM Passive Optical Networks (PON)

DWDM passive optical networks (PON) use the wavelength channels to connect the users with the central office. Each service uses one wavelength channel. The early PON was developed for narrowband services, such as the PON architecture developed by British Telecom. However, recent PONs are for both broadband and narrowband services.

A passive subscriber loop is attractive because it uses no active devices outside the central office (CO), except at the customer premises. Several architectures of passive optical networks have been proposed for WDM or DWDM, which include the single-star, the tree, the double-star, and the star-bus.

Figure 7 shows the single-star architecture in which each household has a dedicated fiber to the central office (CO). The WDM channels in the fiber are used to carry all required services, such as voice and video. This architecture is designed for easy installation and upgrading; however, the cost of dedicated optical fiber between the customer and the CO in this network is still a major concern. Thus, this architecture may not be suitable for widespread deployment in the near term.

Figure 8 shows the tree PON architecture, in which the DWDM channels are split in the way of tree branches with each user having one or more wavelength channels. This architecture reduces the fiber use in comparison with the single-star. It is a better architecture, especially for DWDM-based system in which a large number of wavelength channels are available. This architecture can satisfy the customer needs for both narrowband and broadband services. One drawback of this network architecture is its rigidity, in terms of network upgrading.

The star-bus architecture can be considered as a variation of the tree architecture, which improves the flexibility of the tree architecture.

Figure 9 depicts the double-star PON architecture. This architecture provides more flexibility in comparison with the star-bus architecture. It

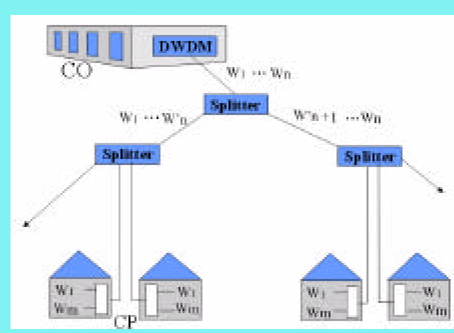
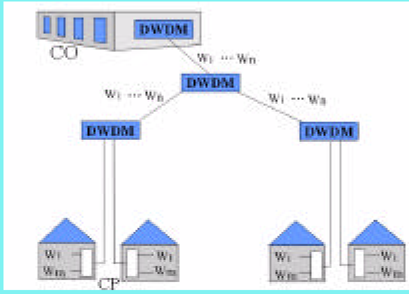


Figure 8: Tree PON architecture

Figure 9: The double-star PON architecture



can be considered as the front-runner among the possible architectures of PON for residential access applications.

3.3 DWDM Active Access Optical Networks

In the passive DWDM access networks, each wavelength channel is used to provide one service at a given time regardless of the channel capacity and bandwidth requirement of the service. With the increasing bandwidth capacity of DWDM technology, the bandwidth of one signal channel becomes high enough to carry several or many services even in the access environment. This leads to the thinking of applying TDM in each individual DWDM wavelength channel, resulting in the active DWDM access optical network in which TDM is used within each channel to provide integrated services. The Asynchronous Transfer Mode (ATM) has been proposed as the TDM protocol in the active DWDM access networks. With the ATM coming into the picture, the original B-ISDN (Broadband Integrated Services Digital Network) protocols are again surfacing in the access network arena. But this time, only one wavelength channel replaces the whole optical fiber in the system.

The network topologies for the passive DWDM access network discussed in the previous subsection can also be used for the active DWDM access network.

Although an active DWDM access network provides high utilization of the wavelength channels and in return reduces the fiber costs, it adds additional costs because of the ATM devices in the system from CO to user premises. It also increases the complexity of system management and maintenance, which leads to high operating costs.

Another twist in this hard-to-decide matter is the birth of the very high channel-count DWDM, in which thousands of wavelength channels are created and transmitted with one fiber. Essex Corp. has reported a 4,000-channel DWDM system. This may make the active DWDM access network architecture lose its potential advantages, and make the passive high channel-count DWDM PON become the leader in the race of access network architectures.

4.0 Concluding Remarks

This article provides an overview of the DWDM applications in two networks, the backbone network and the access network. The DWDM point-to-point technology has already played an important role in the backbone networks and it will continue to be installed for existing and new fiber links. However, for the all-optical DWDM network to become viable, we may have to wait till the optical processing power becomes available. This may create a time gap between the DWDM point-to-point applications and the all-optical DWDM transparent networks. In the access network case, it is still not clear whether the passive or the active is the leader. Although the cost barrier has been weakened through replacing the fiber by DWDM channels in the active access network architecture, the TDM devices in the system may still be too high at the present time. On the other hand, the fiber cost (along with the costs of the passive devices) in the passive architecture is probably still not cheap enough to make it ahead of the active architecture. However, the very high channel-count DWDM may change the landscape of the access network world, and it may become even cheaper than the combined costs of twisted pair copper and coaxial cables.

5.0 Acronyms

ATM	- Asynchronous Transfer Mode
B-ISDN	- Broadband Integrated Services Digital Networks
DWDM	- Dense Wavelength Division Multiplexing
SDH	- Synchronous Digital Hierarchy
SONET	- Synchronous Optical Network
TDM	- Time Domain Multiplexing
WDM	- Wavelength Division Multiplexing
CO	- Central Office
CP	- Customer Premises

6.0 References

[1]. P.E. Green, Jr., "Optical Networking Update", IEEE Journal on Selected Areas in Communications, Vol.14, No. 5, June 1996, pp. 764 - 778.

[2]. J.D. Angelopoulos, et al, "TDMA Multiplexing of ATM Cells in a Residential Access SuperPON", IEEE Journal on Selected Areas in Communications, Vol.16, No. 7, Sep. 1998, pp. 1123 - 1133.

[3]. I. P. Kaminow, et al, "A Wideband All-Optical WDM Network", IEEE Journal on Selected Areas in Communications, Vol.14, No. 5, June 1996, pp. 780 - 799.

About the author

Shaowen Song received a B.Sc. degree in electrical engineering and a M.Sc. degree in applied mathematics from Tianjin University in China. He received his Ph.D. in engineering from Memorial University of Newfoundland.

He is an assistant professor in the Department of Physics & Computing at Wilfrid Laurier University, Waterloo, ON. He was previously an assistant professor in the Department of Mathematics and Computer Science at the University of Prince Edward Island, PEI.

His current research interests include broadband access networks, residential gateways, optical logic & computing, and DWDM networks. He is a member of the IEEE Communications Society.

IEEE announces awards to Acadia first-year Electrical Engineering and Computer Science students

November 8, 2000 - Acadia University, Wolfville, NS. The Canadian Atlantic Section of the Institute of Electrical and Electronics Engineers (IEEE) today announced an award of $100 each to the students with the highest final grade in two first-year Engineering and Computer Science courses at Acadia.

Students of COMP 1213 (Digital Systems) and APSC 2213 (Electric Circuits) will compete for the two awards.

A presentation will be made to the winners during Engineering Week activities in March 2001 at which time the winning students will each also receive a free one-year student membership in the IEEE. Presented in collaboration with the Acadia University student branch of the IEEE, this award is designed to increase awareness among Engineering and Computer Science students of the IEEE and its activities.

On hand for the announcement were Dr. André Trudel, Director, Jodrey School of Computer Science and Dr. Andrew Mitchell, Director, Ivan Curry School of Engineering, Mr. Brian Maranda, Chair of the Canadian Atlantic Section, IEEE, as well as several representatives of the Canadian Atlantic Section of the IEEE.