♦ The Wavelength Add/Drop Multiplexer for Lightwave Communication Networks

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Lightwave systems are progressing toward optical networks capable of manipulating data paths by optical means rather than by traditional electronic switching. This is facilitated by wavelength multiplexed transmission, in which narrow bandwidth optical filters can be used to remove specific channels and reinsert new ones anywhere in the optical link. Wavelength add/drop multiplexers performing this optical channel processing can range in capability from providing dedicated add/drop of a single channel to having fully reconfigurable add/drop of many, if not all, of the wavelength division multiplexed (WDM) channels. Careful placement of wavelength add/drop multiplexers can dramatically improve a network's flexibility and robustness while providing significant cost advantages. This paper summarizes the rationale for incorporating wavelength add/drop multiplexers in modern optical networks, outlines their logical and optical characteristics, and introduces the predominant technology choices.

Introduction

The astonishing demand for lightwave communication networks has spawned aggressive efforts to invent desperately needed optical components and subsystems. In this paper, we will concentrate on wavelength add/drop multiplexers (WADMs)—versatile optical subsystems that facilitate the evolution of lightwave systems from single-wavelength point-to-point transmission lines to wavelength division multiplexed (WDM) optical networks. The need for greater flexibility in wavelength management is apparent considering the enormous transmission capacity of optical fibers that can carry hundreds of WDM channels. The resultant fiber capacity, now in the terabit/second range, can exceed that required to simply connect two network nodes; more economical fiber utilization is needed. WADMs facilitate management of fiber capacity by enabling the selective removal and reinsertion of WDM channels at intermediate points in the line system. There are also many new advantages for provisioning and protecting a network by manipulating the optical granularity created by the wavelength multiplexing of channels.

Lucent Technologies' WaveStar™ 400G optical line system (OLS)—an 80-channel, 400-Gb/s aggregate capacity system—exemplifies the introduction of WADM technology. Initial deployment of WaveStar 400G will have a fixed 4-channel add/drop capability dispersed along the optical link, and later releases will include a 16-WDM-channel rearrangable add/drop multiplexer. Similar capabilities are expected from other lightwave system manufacturers as optical networks evolve to capitalize on the advantages of wavelength multiplexed signals.

Metropolitan WDM lightwave services constitute another area of intense activity where interoffice and business premises wavelength add/drop plays an important role. Proposals range from rearrangable add/drop management of 1 to 8 channels in a small business access ring to complete add/drop management of 40 or more channels in an interoffice ring. Furthermore, each WDM channel may carry different data rates and formats as expected in a shared media serving diverse business needs. This breadth of applications and the urgency to deploy WADMs demand a

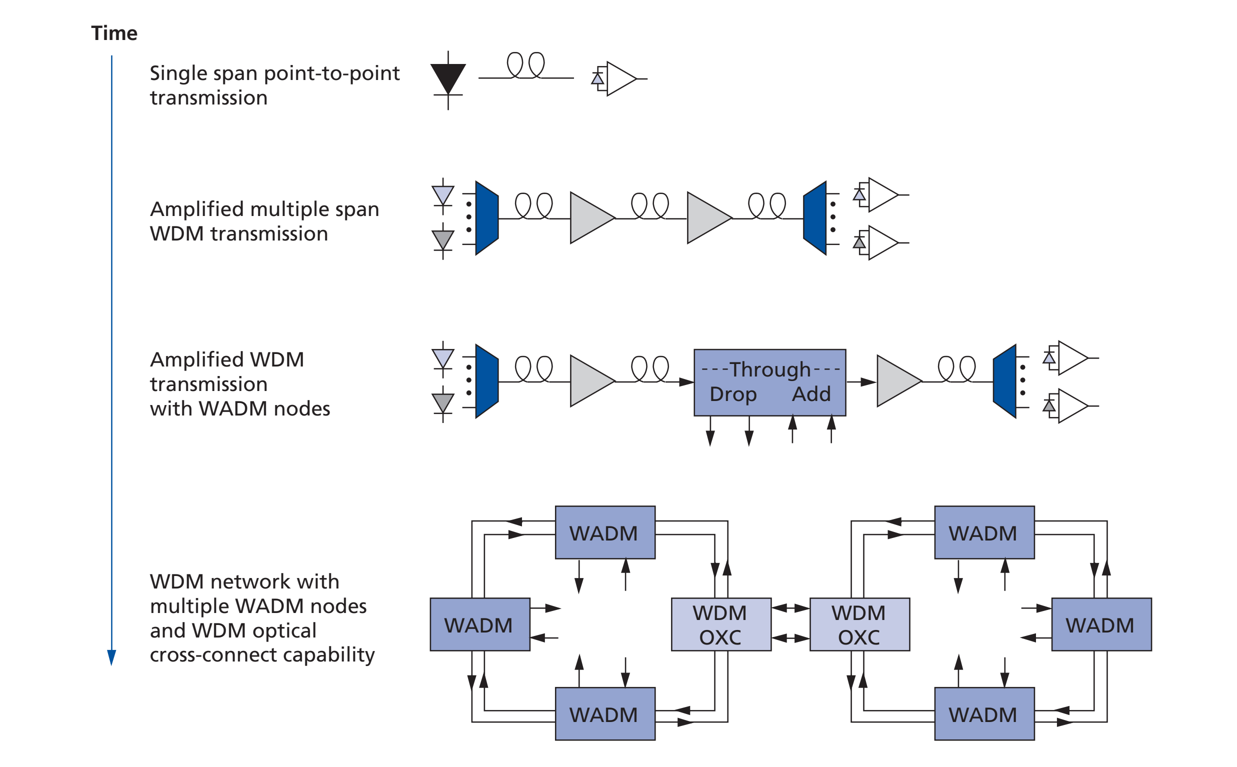


Figure 1.
Evolution of fiber-optic transmission from single-span transmission to optical networking.

methodical evaluation of technology options similar to that which we will develop in this paper.

To illustrate where we have come from and where we are headed in lightwave communications, **Figure 1** depicts the evolutionary course of fiber-optic systems and networks, beginning with single-channel point-to-point transmission systems and leading to optical networking. Ten years ago, a long distance fiber-optic transmission system consisted of a series of optical transmitters and receivers linked through short fiber spans. The individual span lengths rarely exceeded 40 km since laser transmitter power was limited to 1 mW, and practical optical amplifier repeaters were unavailable. Consequently, at that time the main benefit to incorporating multiple WDM channels in a single fiber was to increase the overall optical

Panel 1. Abbreviations, Acronyms, and Terms

MONET—Multiwavelength Optical Networking
NRZ—nonreturn to zero
OC-192—optical carrier digital signal rate of 9.953 Gb/s in a SONET system
OC-48—optical carrier digital signal rate of 2.488 Gb/s in a SONET system
OLS—optical line system
RF—radio frequency
SONET—synchronous optical network
SPM—self-phase modulation
WADM—wavelength add/drop multiplexer
WDM—wavelength division multiplexed/multiplexing
WIS—wavelength-independent switch
WSS—wavelength-selective switch

Panel 2. Nomenclature of WADMs

Add-channel: WDM channel inserted locally, appearing at the out-port WDM stream.

Add-port: WADM input port carrying channels to be added to the optical stream appearing at the out-port.

Branching function: The capability of selecting one or more dropped WDM channels to exit from a single drop-port.

Drop-and-continue function: The capability to simultaneously drop and continue (pass on to the out-port) a particular WDM channel through the WADM.

Drop-channel: WDM channel removed from the in-port WDM stream.

Drop-port: WADM output port carrying channels removed from the input optical stream.

East-west separability: A design specification requiring that the reliability, maintenance, and upgrade of the in- and drop-ports be autonomous from that of the out- and add-ports. East-west separability prevents unprotected failures and maintenance procedures that could otherwise occur in some optical networks.

Fixed WADM: A WADM permanently configured to drop, add, and express preassigned WDM channels.

Flexible WADM: A WADM that can be scaled with minimum intervention to accommodate varying numbers of add/drop channels. An example is a set of serially connected single-channel WADM modules. Both fixed and reconfigurable WADM may be flexible.

In-port: WADM input optical port.

Noninterrupting reconfigurable WADM: A reconfigurable WADM that interrupts service during reconfiguration only on the WDM channels being reconfigured.

Optical through: WDM channels propagate through the WADM only as optical signals.

Optoelectronic through: WDM channels propagate through the WADM with optical-to-electrical-to-optical conversion.

Out-port: WADM output port carrying the output optical stream altered by the add/drop function.

Reconfigurable WADM: A WADM that can be reconfigured—manually or automatically—to change the drop, add, and express conditions for various WDM channels.

Remotely reconfigurable WADM: A WADM that can be programmatically reconfigured through the network software to change the drop-, add-, and through-states for various WDM channels.

Through- (continue-, express-) channel: WDM channel carrying the same information payload from in-port to out-port of the WADM.

WADM input state: The state defined by the channels present at the in- and add-ports of the WADM.

WADM node operational state: The state of the WADM node defined by the input and output states and the connection matrix C.

WADM output state: The state defined by the channels present at the out- and drop-ports of the WADM.

Wavelength-reuse WADM: A WADM that accommodates drop- and add-channels at the same wavelengths.

transmission capacity. The introduction of WDM transmission was challenging as it required new optical components (multiplexers, demultiplexers, and improved laser sources), and there was strong competitive pressure from increasing single-channel (time division multiplexing and optical time division multiplexing) bit rates. Transmitting farther than 40 km raised unavoidable costs as signals had to be processed through expensive optoelectronics on a per-wavelength channel basis.

The discovery of erbium-doped fiber amplifiers provided compelling reasons to employ WDM signaling. With optical amplifiers, optical transmission reach was extended to thousands of kilometers, allowing widely separated regions to exchange large quantities of voice and data at a reasonable expense. Technology

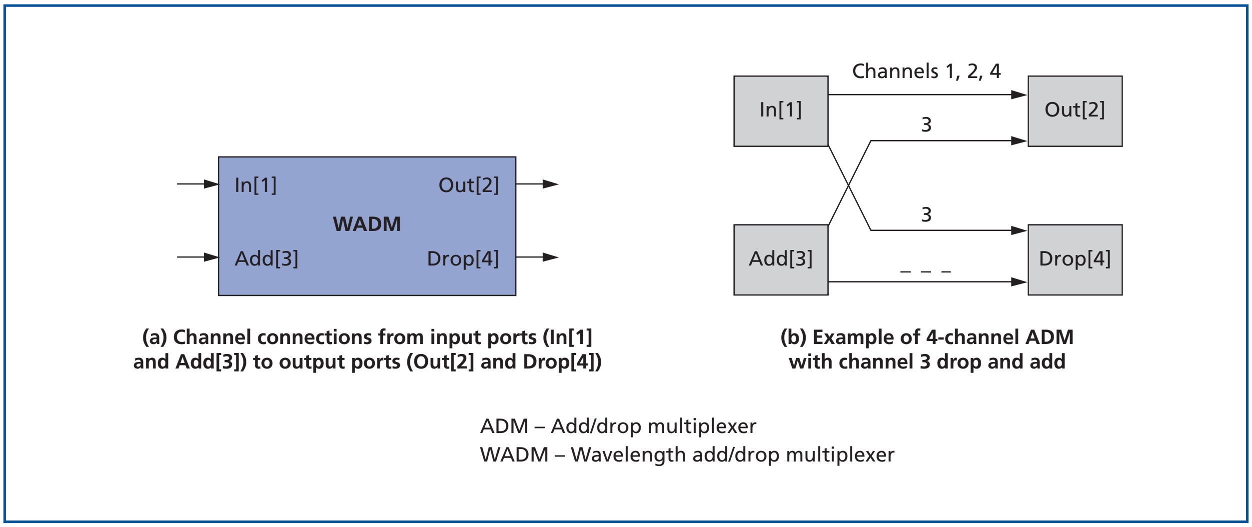


Figure 2.
Four-port model of the WADM.

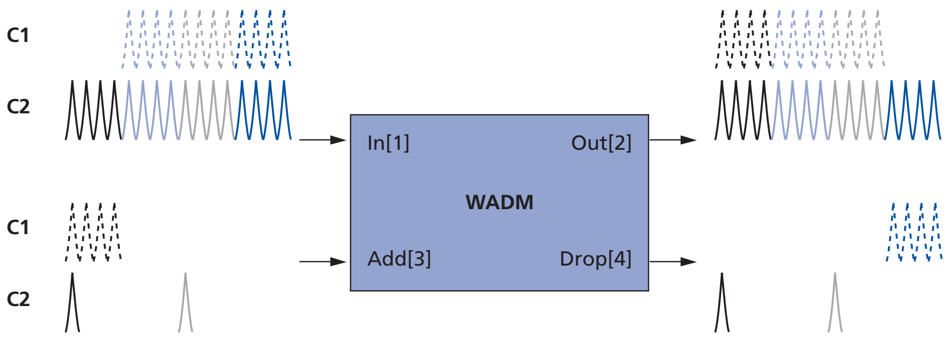
has also responded to the demands for higher capacity, and terabit/second transmission on a single optical fiber is now feasible.[1] While petabit/second data exchange in dense metropolitan areas has been considered,[2] near-term expectations are for data exchange rates between major centers to be around a terabit/second, commensurate with the capacity of a single optical fiber. The WADM enables greater bandwidth efficiency by allowing this capacity to interconnect geographically diverse centers along the fiber transmission link. Inefficient loopback of data streams to smaller nodes between major nodes can also be avoided.

The WDM channels used to communicate between nodes in a network can be permanently provisioned or adapted to changing network conditions. A fixed WADM is appropriate in the first case, facilitating the removal and reinsertion of data streams on dedicated WDM channels. This capability—fixed wavelength add/drop of selected channels—is the state of the art for commercial systems in 1999. Reconfigurable wavelength add/drop—the ability to manually or programmatically alter the wavelength connections through the WADM—has been widely demonstrated and sought for imminent deployment. Flexible optical provisioning—the ability to set up and tear down wavelength connections to follow traffic demands in a network for efficient capacity utilization—is one advantage of reconfigurable add/drop multiplexers. Reconfigurable WADMs can also be used for optical restoration, providing the ability to reroute traffic around failed lines or nodes. Details concerning provisioning and restoration using WADMs are vague, as they must consider the full network, not just the behavior of the WADM. For example, synchronous optical network (SONET) rings already incorporate protection mechanisms through spare channels and fibers, and the interaction with optical protection using a WADM must be understood. We will not attempt to resolve these network issues in this paper; instead, we will focus on describing the WADM as an optical component and introducing a few of the predominant technology choices.

Functional and Logical Descriptions of the WADM

The complexity inherent in lightwave optical networks and subsystems is captured in the nomenclature describing their function and operation. For this discussion, we adopt a vocabulary to distinguish key attributes of WADMs in order to associate WADM characteristics with their functions in the network. The definitions, listed in **Panel 2**, also help to classify the technology options as viewed from the perspective of system architecture.

A wavelength add/drop multiplexer is characterized in terms of total numbers of input-, through-, drop-, and add-*channels* (WDM data streams). The



		Channel	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16
C1	Port connection	1-2	0	0	0	0	1	1	1	1	1	1	1	1	0	0	0	0
		1–4	0	0	0	0	0	0	0	0	0	0	0	0	1	1	1	1
		3–2	1	1	1	1	0	0	0	0	0	0	0	0	0	0	0	0
		3–4	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
C2	Port connection	1-2	1	0	1	1	1	1	1	1	1	1	0	1	1	1	1	1
		1–4	0	1	0	0	0	0	0	0	0	0	1	0	0	0	0	0
		3–2	0	1	0	0	0	0	0	0	0	0	1	0	0	0	0	0
		3–4	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0

WADM – Wavelength add/drop multiplexer

Figure 3.
WADM connection diagram.

function of the WADM is defined in terms of the WDM connections among its optical *ports* (physical input and output optical paths), including the ability to rearrange the connections. These considerations lead to a formal matrix description of the connectivity from input to output ports, which assists in the unambiguous classification of the logical characteristics of a WADM. **Figure 2** shows a WADM having in-, out-, add-, and drop-ports numerically designated from 1 to 4. It is implicit that there are m add- and drop-ports available ($m \le N$) to implement full add/drop capability with ports available for each channel. Later, we will distinguish between the "wavelength-selective-switch-centric" WADM in Figure 2 and the "space-switch-centric" WADM that inherently multiplexes the add-channels and fully demultiplexes the through- and drop-channels. Channel pathways are indicated from the in- and add-ports to the out- and drop-ports—the logical traffic directions normally associated with the WADM. A connection matrix is constructed with rows corresponding to optical paths through the WADM and columns of 0s and 1s indicating the state of connections for each WDM channel. A fixed WADM is represented by a single connection matrix while a reconfigurable WADM is represented by a set of matrices. A fully flexible WADM that can add/drop any and all of N channels has at least 2^N possible connection states (more than 2^N are possible if the in- and add-ports can independently connect to the out- and drop-ports). **Figure 3** shows two representative connection matrices—C1 and C2—for 16 WDM channels in a WADM. In C1, channels 5 to 12 are

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