Invited Paper

Photonic add-drop multiplexing perspective for next generation optical networks

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ABSTRACT
An add/drop multiplexer (ADM) is recognized as one of the basic building blocks to extend DWDM networks from a static point-to-point system into a next generation, dynamic, re-configurable, programmable optical network. The objective of this paper is twofold: (1) provide an extensive overview tutorial of the numerous existing implementations of ADM, (2) categorize these different ADM implementations, and (3) assess their respective limitations and impacts on an evolving optical network. Toward this goal, a clear distinction between an OADM and a WADM node is made in terms of add/drop port configuration using a functional black box approach, and the types of component and device technologies that support these structures. Our second objective is to use this classification scheme to project, what we believe, is the functional form of the next generation ADM module. This is accomplished by taking into account major trends and developments in the optical networking arena. Lastly, some technical perspectives and directions toward the form of the next generation ADM are presented.

Keywords: add and drop multiplexer, optical network,

1.0 INTRODUCTION

An add/drop multiplexer (ADM) is an essential and enabling device in the rapidly developing dense wavelength division multiplexing (DWDM) optical fiber communication networks [1]. ADM is recognized as one of the basic building blocks to extend the DWDM network from a static point-to-point system into a next generation, dynamic, re-configurable, programmable optical network. ADM provides, *in its very fundamental form*, the function of selectively removing and adding a number of wavelength channels without disrupting the other propagating wavelength channels being carried by a DWDM transport line. The dropped channels are then available either for regeneration purposes or access by client terminals.

In technical and commercial literature, ADM is commonly referred to by many different terms. Two such familiar terms are Optical Add and Drop Multiplexer (OADM) and Wavelength Add and Drop Multiplexer (WADM). Often, these two terms are used interchangeably. Moreover, ADM is oftentimes discussed in *two different functional contexts or levels* without any clear clarification. These two contexts are either as (a) optical module, on one hand, and (b) network node, on the other hand. Although this vagueness does not lead to actual technical difficulties, it sometimes introduces confusion. In this paper, we will differentiate OADM from WADM, and state clearly the context in which they are used. We will also concentrate more on the dynamic implementations of ADM rather than static ADM.

1.1 Functional context of ADM:

Fig. 1 shows the interplay of three important levels related to ADM namely: (1) ADM as an optical module, (2) ADM as a network element or node, and (3) ADM node within an optical ring network. ADM-as-optical-module is the central element in any ADM network node. At this level, there are numerous reported implementations to obtain the basic add and drop function of a selected wavelength channel. Generally speaking, the particular choice of implementation greatly determines the overall architecture and performance of the ADM as a network node. As shown in the upper portion in Fig. 1, ADM-as-network-node is generally positioned between two network terminals or nodes or at any intermediate location within the optical ring networks where local access to only a fraction of the propagating wavelength channels is required.

In order to maximize the performance of the optical network, it is desirable that ADM possesses both (1) excellent optical module properties, and (2) well engineered network node characteristics. At the module level, the optical properties of ADM should approximate the following ideal features namely: (1.1) unity transmission, flat-top, nearly zero-ripple frequency response over the pass-through spectrum, (1.2) infinite rejection ratio over the drop spectrum, (1.3) sharp roll-off or steepness in between the add and drop spectrum, (1.4) negligible phase dispersion on the pass-through or drop wavelengths, (1.5) high isolation of all pass-through wavelength channels from transient negative effects of a tuning filter (also known as “hitless”) , (1.6) low insertion loss, and (1.7) negligible polarization mode dispersion (PMD) & polarization dependent loss (PDL) values. Deviations from these ideal properties impact the quality of the output optical signals leaving an ADM network node.

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As a network node, ADM should be designed not only to provide basic add-and-drop capability but also to deliver other essential node characteristics such as; (2.1) scalability in number of drop wavelength channels and bit rate, (2.2) modularity, (2.3) efficient wavelength utilization, (2.4) optical performance monitoring, (2.5) fault detection and isolation, (2.6) optical amplification, (2.7) channel power equalization, (2.8) optical layer protection, (2.9) redundancy, and (2.10) service restoration. Besides these optical node characteristics, ADM node might also contain electrical node functionality such as (2.11) 2R/3R regeneration, (2.12) bit rate adaptation, and (2.13) grooming. All these requirements should be met at

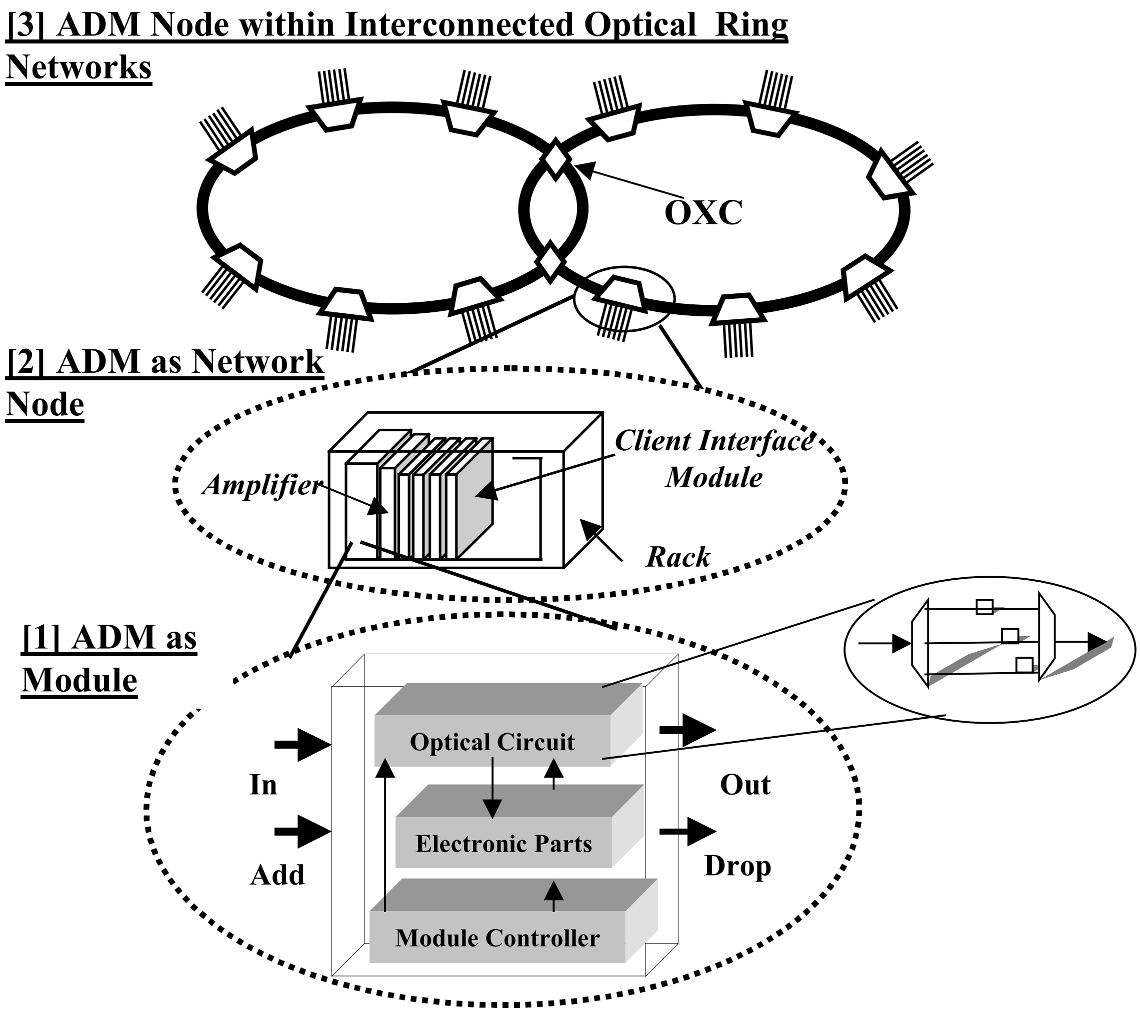

Fig. 1. ADM-as-optical-module is part of ADM network node which is positioned between two other network nodes of interconnected optical ring networks.

the minimum cost while maintaining high quality signal. These node characteristics or requirements have dual consequences. First, they constraint the design of ADM-as-module. Secondly, they define in large part the optical ring network's survivability, quality of service, and over-all performance.

At the network level, the topology of the actual optical networks and network upgrade path designs, (among other things such as economic viability, etc) put a general framework on which these ADM nodes and ADM modules must be designed and optimized. Ideally, this framework can be considered from day one, but in practice, the overall network is still evolving and its "evolutionary form" is still not yet clear. The need to continuously track this network trend, meet new demands and respond appropriately lead the telecom industry to introduce, build and deploy next generation ADM nodes or next generation ADM modules.

1.2 Functional relationship between ADM and OXC

Although this paper is focused on ADM, it is important to point out the functional relationship between ADM and cross-connect (XC). As shown in the upper portion of Fig. 1, an example of optical network of the kind that we are

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considering consists of two optical fiber rings which are interconnected by a network node commonly known as XC. Functionally speaking, a XC routes or transfers any optical signals coming from any input fiber ports of either optical ring to any output fiber ports of either ring. This interconnection is not limited to optical rings but can be extended easily to mesh topology with the XC having greater degree of connectivity. Furthermore, XC can, in general, also provide add/drop functionality for all connected fibers. XC is considered functionally more general than ADM. XC and ADM are generally regarded as two distinct network nodes. But in principle, ADM is the simplest form of XC having one degree of node connectivity.

As the optical network topology evolves from simple ring to multiple interconnected rings, and finally to mesh, a corresponding evolution on ADM will also occur. In this paper, we will also touch on the functional evolution of ADM from a typical ADM node towards a more sophisticated ADM-based XC.

1.3 Objectives of the Paper

In order to have a clear understanding of present ADM nodes, possible architectures of the next generation ADM nodes, and future functional relationship between ADM and OXC, it is essential to have a comprehensive overview of the different existing implementations of ADM-as-module. However, due to the enormous number of reported ADM module designs and a lack of clear classification method, it is oftentimes difficult to assess their respective limitations and impacts on the ADM node, and eventually to the evolving optical transparent network. In this paper, our objective is twofold. First, we present an extensive overview tutorial of the different existing implementations of ADM modules, and categorize them using a new, simple but powerful classification scheme. Toward this goal, a clear distinction between an OADM from a WADM is made in terms of (1) add/drop port configuration using a functional black box approach and (2) the types of component and device technologies that support these structures. Our second objective is to use this classification scheme to project, what we believe, is the functional form of the next generation ADM module. This is accomplished by taking into account major trends and developments in the optical networking arena. We will refer to this future ADM module as Photonic ADM (PADM). The relationship of the OXC and PADM will then be evident from the discussion in the paper.

This paper is organized as follows. First, we introduce our classification scheme in section 2.0. Then we present the hierarchy of an ADM. The comparison and discussion of existing OADM implementations are given in section 3.0. The corresponding discussion for WADM implementations is given in section 4.0. We offer our perspective on the next generation ADMs with an explanation of PADM in section 5.0.

2.0. GENERAL CLASSIFICATION OF ADM

The numerous existing and proposed optical module-based ADMs can be classified in many different ways. Generally speaking, they have been classified according to whether they are (a) static or dynamic ADMs, (b) serial-based or parallel-based ADMs, (c) single-function- or multiple-function-based ADMs, (d) add/drop wavelength count capability (high, moderate, or low), and (e) technology specific-ADMs.

In this paper, these different ADM implementations are classified rather uniquely and unconventionally. ADMs are classified based on their add/drop port physical configuration**.** The port configuration of any ADM will be defined by the following convention, **(N x L) x 2D** where (N x L) represents N input ports, L output ports that are designed to accept *only* multiplexed signals, and D denotes add-and-drop port pairs that are engineered to accept *only* per-λ signals or wavelength-banded signals or both. When D is equal to zero, the ADM is simply referred to as a (N x L) module. In order to add M numbers of wavelengths that an ADM module is designed to operate, the notation will be refined to a *M-wavelength* channels x (N x L) optical module.

Using this classification, the numerous ADM implementations can be grouped into three general classes as shown in Fig. 2. Within the context and confine of this paper, we will refer to the first class and second class of ADMs as OADM, and WADM, respectively. The third class will be called PADM. From our discussion, it will become more apparent why these labels are appropriate. As shown in Fig. 2, the OADM has *M-wavelength channels x (2 x 2)* port configuration where (2x2) stands for *one input port*, *one output port*, *one multiplexed add port*, and *one multiplexed drop port*. Functionally, it accepts multi-wavelength input signals at the *main input port*, selects **S** number of discrete, arbitrary wavelength channels, directs them to the *primary drop port*, adds new **S** number of discrete wavelength channels through *a primary add port*, and finally recombines the resultant multi-wavelength signals before they exit the ADM at the *main output por*t.

On the other hand, a WADM is configured as a *M-wavelength channels x (1 x 1) x 2K* optical module where (1x1) stands for *one main input port*, one *main output port* and 2*K number of secondary add and drop ports*. These 2K ports are meant to individually access the **K** add/drop per-wavelength channels. The add/drop ports have pre-determined, fixed wavelength assignments. Note that an OADM can be transformed functionally to a WADM by two different approaches. The simplest way is to connect external demultiplexers (Demuxes) and multiplexers (Muxes) to the drop and add ports of OADM,

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respectively. Likewise WADM can be converted to OADM in the same manner. The advantages and disadvantages of doing this approach will be discussed in section 4.0.

While OADM and WADM represent most existing and proposed ADM optical modules, the third class is what we believe to be the "functional form" of the next generation ADM. PADM is a combination of OADM and WADM with some extra new capabilities. It is a *M-wavelength channels x (2 x 2) x 2(K+B)* optical module where (2x2) stands for the same structure as OADM, and the 2*K stands for the numbers of secondary add and drop ports just like the WADM*. However unlike the WADM, these secondary ports take in wavelength-banded signals (which are represented by **B**) as well as per-wavelength signals (which are represented by **K**). The thick slash lines in the input / output arrows represent wavelength-multiplexed signals while the thin slash lines in the secondary ports denote wavelength-banded signal. Wavelength-banding consists of 4 or more adjacent wavelength channels per band. Functionally, PADM-as-module has expanded capability compared with conventional OADM and WADM. Table 1 provides the general features of these three classes of ADMs. A more detailed discussion of PADM is given in section 5. As a network node, ADM would contain two or more ADM-as-optical-modules to provide dual directions for the east and west transmissions. Note that Fig. 2 shows only unidirectional transmission and extension to bi-direction propagation would be straightforward.

The distinction between OADM, WADM and PADM has many significant beneficial consequences. For one, it provides a general platform to classify, segment, and compare the numerous existing technical implementations of ADM in a coherent and comprehensive way. Secondly, it identifies the respective applications of the different ADM implementations based on their technical merits and demerits. Lastly, it would help us to understand the current technical trend and gain insight to the next generation ADMs.

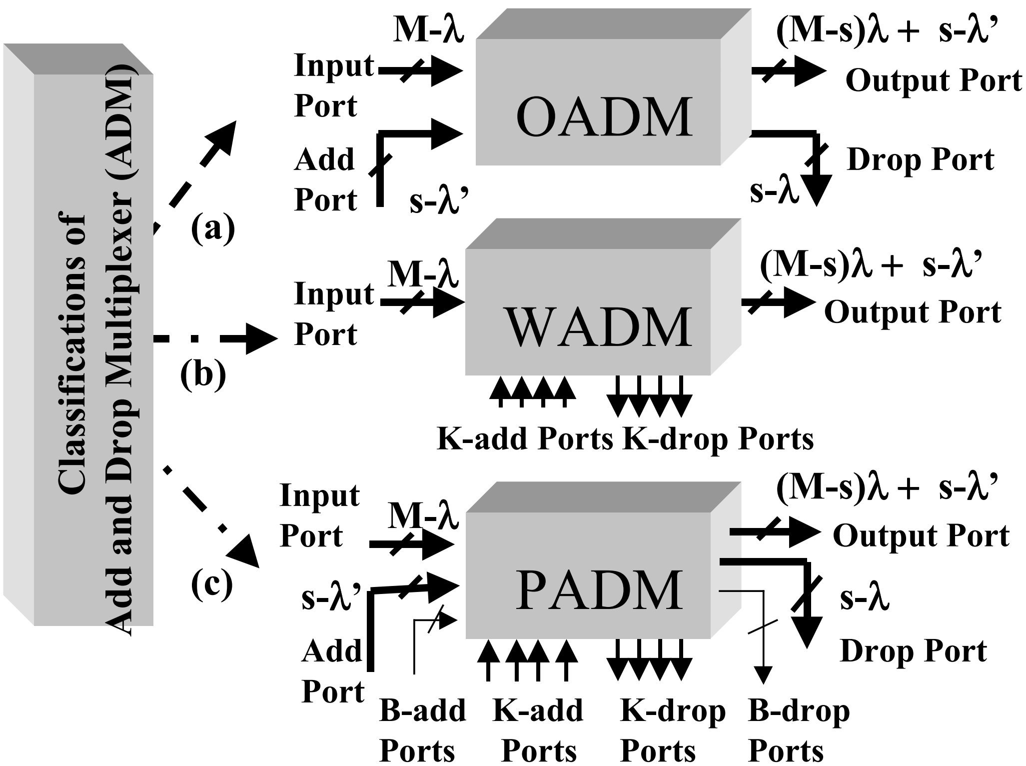

Fig. 2. Three different groupings of add and drop multiplexer (ADM as optical module) according to their functional port configurations. Photonic ADM (PADM) is a combination of both optical ADM (OADM) and wavelength ADM (WADM) with new and extended functionality. S-λ' and S-λ represent the number of add and drop wavelengths, respectively. The thick slash lines in the input / output arrows (in all ADMs) represent wavelength-multiplexed signals while the thin slash lines in (PADM only) secondary ports represent wavelength-banded signals. Only one direction of the transmission is depicted.

3.0 HIERARCHY OF ADM

With this classification, OADM, WADM and PADM can be subdivided further into smaller groupings to establish a form of hierarchy of ADMs**.** Here we will concentrate more on the dynamic implementations of ADMs rather than static ADMs. As shown in Fig. 3, this ADM hierarchy consists of 4 layers. The first layer is composed of OADM, WADM and

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PADM groupings. Again, the distinction between these classes is based on the physical port configuration. In the second layer, the different OADM and WADM implementations are categorized broadly into two major groupings based on the physical mechanism involved in the dynamic selection of wavelength(s) to be dropped or added. These two major groupings are called (1) "tuning-based λ-selection", and (2) "switching-based λ-selection". ADM implementations under these two broad groupings can be segmented further into smaller sub-groupings or subsets according to the generic optical structures employed. This is the third layer. The last or fourth layer is based on the actual design implementations.

The detailed discussion of this hierarchy starts with an OADM in section 3.1 and is followed by a WADM in section 4.0. For an OADM, this hierarchy is broken down into a "tuning-based OADM" and "switching-based OADM". We will evaluate these implementations purely on the following issues: (1) level of functionality, (2) component counts for multi-channel operation and configurability, and (3) scalability. Although the technical performance will not be evaluated in detail, we will pin point key parameters that limit their performance. Brief explanation of these different "tuning based OADM" designs are given below. Furthermore, these are briefly summarized and tabulated in Table 2.

Features		**OADM**	**WADM**	**PADM**	**Comments**
Port configuration		(2x2)	(1x1) x 2S	(2x2) x 2S	S stands for secondary wavelength add/drop ports
No. of λ-channel		M	M	M	
Add / Drop Ports					
Primary		1-add, 1-drop ports	none	1-add, 1-drop ports	
Secondary		none	S-add, S-drop ports	S-add, S-drop ports	
Access Granuality					
	multiplexed λ	yes	none	yes	*3 levels of granularity is required for PADM*
	per-λ	none	yes	yes	
	λ– banding	none	none	yes	
Access path to add/drop		Primary ports only	Secondary ports only	Both primary and secondary ports	*flexibility demands dual access for PADM*
K-port vs λ assignment					
	Fixed	none	yes	yes	
	Variable	none	none	supported	*client configurability is required for PADM*
No. of Secondary Ports			Application depended	Application depended	
Transformation of OADM to WADM (and vice versa)					
Approach # 1 (requirements)		2 external Demux / Mux devices	2 external Demux / Mux devices		functionally build-in in PADM
	multiplexing penalty	yes	none		
Approach # 2 (requirements)		Concatenation of OADM units			
Additional Functionality					
"Drop and terminate" functionality			Well-suited	yes	Good for direct client terminal connection
"Drop and continue" functionality		Suited		yes	Good for ring interconnection
Optical Layer Protection					
	Dedicated protection	Need to be engineered at node level		build-in	
	Shared protection	Need to be engineered at node level			
Network Application		Interconnected Optical Ring	Simple Optical Ring with direct Client interface	Simple Ring, Multiple Interconnected Ring, and Mesh	PADM is very appropriate for network evolution because of its flexibility

Table 1. General features of the three different groupings of ADM. Note that wavelength-banding, client configurability, and dual access (primary and secondary ports) to add/drop signal are some of the new requirements for PADM.

3.1 Tuning-based OADM

Tuning-based OADM depends on two fundamental elements: (1) tunable filters to select a particular wavelength(s)

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