Modeling WDM Wavelength Switching Systems for use in GMPLS and Automated Path Computation

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Network control planes have made an implicit assumption that the switching devices in a network are symmetric. In wavelength switched optical networks even the most basic switching element, the reconfigurable add/drop multiplexer, is highly asymmetric. This paper presents a model of optical switching subsystems for use in GMPLS, route selection and wavelength assignment. The model covers a large class of switching subsystems without internal wavelength converters. The model is applied to a number of common optical technologies, a compact encoding for use in the optical control plane is furnished along with a method for deriving a simplified graph representation.

OCIS Codes: 060.4250, 060.4251, 060.4264, 060.4265.

1. INTRODUCTION

Generalized Multiprotocol Label Switching (GMPLS), a suite of control plane protocols, from the outset included some support for wavelength switched optical networks [1]. This support was in the ability to specify the wavelength of an optical signal for each link segment along a path [2] and also to roughly characterize the switching capabilities of a device [3] such as "lambda switching capable" or "waveband switching capable". As pointed out in [4] the existing GMPLS routing specifications did not include enough detail on wavelength utilization nor on properties of wavelength converter pools for optimal routing and wavelength assignment (RWA) which could be accomplished by making use of the recently standardized *path computation element (PCE)* architecture [5] and protocols that can supplement GMPLS. Other recent research in the area of GMPLS technology applied to WSON has included advanced techniques for wavelength assignment via GMPLS signaling to reduce blocking [6], and make more efficient use of wavelength converters [7]. Recently efforts at standard development organizations have returned their attention to the control plane for WSONs [8-10]. One of these efforts sought to increase interoperability by introducing a standard label format [11]. Others have focused on general control plane architectural aspects that prominently feature the use of a path computation element (PCE) for use in optimization and tackling the potentially difficult RWA problem in addition to distributed wavelength assignment based on signaling [10]. In the process of upgrading the GMPLS control plane to better handle optical networks it was noted by Imajuku [10] that a key property of optical network devices, which is referred to as "asymmetric switching", was overlooked. By "asymmetric switching" we mean here a switch where a signal on an ingress port can only reach a subset of egress ports."

Link state routing models for packet switched networks such as OSPF [12] and IS-IS feature symmetric switching nodes and links with relatively simple attributes such as a metric used in shortest path route computations. By “symmetric” switching node we mean here a switch where a signal on any ingress port can potentially reach any egress port. The only state information kept concerning the link is its operational status, e.g., whether it is up or down. Features were then introduced into link state routing protocols to support the extended QoS features of ATM [13] and MPLS [14]. These included link capacity constraints and current utilization state (bandwidth currently used and available). Though the link models increased in sophistication the models for the switching nodes remained that of a simple non-blocking symmetric switch fabric. This assumption stemmed from the original packet switching application of link state routing protocols. Similarly ITU-T network architectural models including those in references [15,16] have as the fundamental indivisible switching subsystem an entity called a “matrix” which is once again assumed to be symmetric in that a signal on any ingress port can potentially reach any egress port. In the early days of optical control plane (GMPLS) the asymmetry of a device such as a ROADM was typically ignored since the add and drop sides were not considered in the overall network topology, however with higher degree ROADMs, colorless add/drop ports, the increased use of drop side inter-connect, and the continuing interest in multi-layer networking [17], the asymmetric aspects of these very common optical switching devices could no longer be ignored.

One approach to generating a model for asymmetrical switching devices is to reveal the inner workings of the switch or multiplexer. Indeed most if not all switching structures in common use today are assembled from a collection of non-blocking fabrics and capacity constrained links [18]. This has two distinct disadvantages. First, the internal structure of switching systems can be quite complicated resulting in a large amount of internal structure and internal state information to be shared concerning the switching node. This large amount of structure and state, cause scalability concerns for the control plane since this information would need to be distributed via an extended GMPLS link state routing protocol. Second, and just as importantly from a standardization perspective, is that the internal structure of switching systems is vendor proprietary information and is not typically shared with other vendors via either the control or management plane. Hence this paper will only address the asymmetric nature of optical switches from a black box perspective that seeks to meet the above requirements for standardization and will not be concerned with the modeling of internal state dependent blocking properties of such switches.

In this paper we first present a general wavelength dependent asymmetric switch model that is independent of internal node state and external link state. We then present a more efficient and compact model that takes advantage of the external link state knowledge needed for RWA calculations and that could be kept by the link state routing protocols extended for WSON. We apply this model to a number of current and emerging WSON switching systems and then show how very general switching systems can be modeled via this approach. We then furnish a compact encoding of the model for transport via the control plane, and then show how this same compact model leads to a minimalistic graph representation for the subsystem.

2. General Asymmetric WSON Switch Model

Since we are not modeling the internal state of a WSON switching system the most general question we can ask of a switch's asymmetric nature is whether a wavelength λ_k on ingress port I_i can be connected to egress port E_j (recall we are modeling switches without wavelength converters). We can represent the potential connectivity between ingress ports and egress ports at wavelength λ_k by a matrix $\mathbf{C}_{\lambda_k} = \{c_{ij}^{\lambda_k}\}$ where $c_{ij}^{\lambda_k} = 0,1$ depending upon whether wavelength λ_k can possibly be connected between ingress port I_i and egress port E_j. This is very similar to an idealization of the *transfer matrices* of reference [19] except that these matrices, in the standards, are applied to a single switching state at a time and the above is used to indicate potential connectivity of a particular wavelength. To fully represent the asymmetrical nature of a WSON switching system we need a collection of such matrices for every wavelength to be utilized in the system, i.e., $\mathbf{C}_{\lambda_k}, k = 1...W$ where W is the number of wavelengths in the WDM system.

3. Simple Model and Application

In wavelength switched optical networks (WSONs) the path computation involves both route selection and wavelength assignment. In the case of limited or no wavelength converters we need more detailed link state knowledge to enable wavelength assignment. Given that we are already keeping this link state information we can use it to model useful devices such as waveband based ROADM which fall outside the scope of the previous formalism and use it to provide a simplified switch model.

As pointed out by Imajuku [10], the most basic aspect of an asymmetrical switching device is that not every ingress port can talk to every egress port. In particular let $\mathbf{C} = \{c_{ij}\}$ denote the *switched connectivity matrix* which indicates whether any wavelength on ingress port I_i can be connected to egress port E_j, i.e., $c_{ij} = 0$ or 1. We now supplement this basic connectivity information with link wavelength constraints on the external links to the switch.

Let $\mathbf{W}_j = \{w_{jk}\}$ be the wavelength usage state for egress port E_j, where

$$w_{jk} = \begin{cases} 0 & \text{if } \lambda_k \text{ is not in use} \\ 1 & \text{if } \lambda_k \text{ is in use} \end{cases}.$$

Suppose we wish to switch a wavelength λ_k on ingress port I_i out of egress port E_j. Now the first restriction of WSON networking is that wavelength λ_k cannot already be in use on egress port E_j, i.e., we require $w_{jk} = 0$. The inclusion of additional egress port wavelength constraints can allow for the modeling of a number of practical WSON switching devices such as a number of different types of reconfigurable add/drop multiplexers (ROADMs) and their generalizations. The following per port constraints types will be demonstrated:

1) Wavelength set constraint: λ_k is required to be an element of a set Λ_j of permitted output wavelengths for egress port E_j. This set can be different for each port.

2) Cardinality restriction: the number of active wavelengths on an egress port is restricted. In equation form $\sum_k w_{jk} \le M$ for egress port E_j.

3) Waveband tuning constraint: the wavelengths in use must fall within a restricted tuning range. $|k-l| \le b_j - 1 \quad \{\forall k,l : w_{jk} = 1, w_{jl} = 1\}$ where b_j is the width of the waveband of egress port E_j in the number of wavelengths.

In the following we will use the preceding formalism to model Type I and II ROADMs, Wavelength Selective Switches (WSS), a waveband based ROADM and a higher degree ROADM (i.e., a system that has both OXC and ROADM features).

A. Modeling a Type I ROADM

In reference [20] a type I ROADM is defined as possessing a line side ingress port, a line side egress port, and a multitude of colored drop ports. Note that this is actually "half" a ROADM since this structure is usually repeated in the opposite direction for a "bi-directional" system. Multiple technologies can be used to realize such systems in particular wavelength blockers (WB) and small switch array (SSA) technologies. A diagram of one possible implementation of such a system based on a SSA is given in Figure 1.

An implementation dependent method of modeling this ROADM would consist of 2 nodes for each of the demultiplexers with wavelength constraints on each demultiplexer output link, 1 node for the output multiplexer, *N* 2x2 switching nodes for each element of the SSA, and one node to represent the input splitter. Instead we can represent this ROADM in general by the $(N+1)\times(N+1)$ connectivity matrix

$$\mathbf{C} = \begin{bmatrix} 1 & 1 & \dots & 1 & 1 \\ 0 & 0 & \dots & 0 & 1 \\ 0 & 0 & \dots & 0 & 1 \\ \vdots & \vdots & \vdots & \vdots & \vdots \\ 0 & 0 & \dots & 0 & 1 \end{bmatrix} \tag{1.1}$$

Where the line side ingress port is labeled port I_1, the add ports are labeled $I_2, I_3, ..., I_{N+1}$ respectively, the drop egress ports are labeled $E_1, E_2, ..., E_N$ respectively, and the line side egress port is labeled E_{N+1}.

The (trivial) port wavelength constraints for the drop ports E_j are:

$$\Lambda_j = \{\lambda_j\} \tag{1.2}$$

and

$$\sum_k w_{jk} \leq 1 \quad (1.3)$$

Equation (1.2) tells us that the set of permissible wavelengths for this port consists of just one member (the definition of a colored port) and equation (1.3) is a redundant, in this case, cardinality constraint that tells us this is a single channel port.

B. Modeling a Type II ROADM

In reference [20] a type II ROADM is defined as possessing a line side ingress port, a line side egress port, and a multitude of colorless drop ports. However these drop ports are restricted to carrying only a single channel. One possible implementation of a type II ROADM is shown in **Figure 2.**

The potential connectivity matrix is given by equation (1.1). The port wavelength constraints for the drop ports E_j are:

$$\Lambda_j = \{\lambda_1, \lambda_2, \ldots, \lambda_N\} \quad (1.4)$$

and

$$\sum_k w_{jk} \leq 1 \quad (1.5)$$

C. Modeling a Waveband based ROADM

Here we consider a waveband based ROADM with line side ingress and egress ports and one waveband drop port per direction. Such a ROADM may be used to branch out a band of wavelengths to another location or for local drop by using single fixed channel or tunable filters after the waveband drop ports. The constraint on the drop ports that defines this type of ROADM is that the wavelengths need to fall within a restricted wavelength range. However, both the width and the central wavelength of the dropped waveband are tunable. In Figure 3 a waveband ROADM, with two bidirectional line side ports and two bidirectional add/drop ports, is depicted.

The connectivity matrix, C={c_{ij}}, in the above example is:

$$\mathbf{C} = \begin{bmatrix} 0 & 1 & 1 & 0 \\ 1 & 0 & 0 & 1 \\ 1 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 \end{bmatrix} \tag{1.6}$$

Below is an example of a drop port, E_j, where the waveband has a width of up to 8 wavelengths. Since the central wavelength of the waveband is tunable, Λ_j, for the drop port includes the same set of wavelengths allowed on the line ports. This leads to the initial state and constraints shown in Figure 4 and equations below:

$$\begin{gathered} \Lambda_j = \{\lambda_1, \ldots, \lambda_N\}, \quad \sum_k w_{jk} \le 8, \\ |k - l| \le 7 \quad \forall k, l : w_{jk} = 1, w_{jl} = 1 \end{gathered} \tag{1.7}$$

When the first wavelength, λ_{first}, has been allocated it restricts the range from which wavelengths can be allocated next. Information about both the waveband tuning constraint and the current wavelength usage state is therefore needed to know which wavelengths can be allocated next. The waveband tuning constraint is illustrated by the window below the wavelength grid for the first three allocated wavelengths in Figure 5. Also seen in this figure are the available wavelengths after each wavelength allocation. In this example the waveband's position on the ITU grid will be fixed after the third allocated wavelength.

D. Modeling a WSS and higher degree ROADMs

The wavelength selective cross connects and higher degree ROADMs can be built from Wavelength Selective Switch (WSS) elements [20]. References [21] and [22] discuss two different approaches to higher degree ROADMs. One based on per port add/drop, as represented in **Figure 6**, and the other based on a per node add/drop, as represented in **Figure 7**.

The connectivity matrix for the ROADM of **Figure 6** is:

$$\mathbf{C}_P = \begin{bmatrix} 1 & 1 & 0 & 0 & 0 & 1 & 1 & 1 \\ 1 & 1 & 1 & 1 & 1 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 & 0 & 0 & 0 & 0 \\ 1 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 1 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 1 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \end{bmatrix} \tag{1.8}$$

The connectivity matrix for the ROADM of **Figure 7** is:

$$\mathbf{C}_N = \begin{bmatrix} 1 & 1 & 1 & 1 & 1 & 1 & 1 & 1 \\ 1 & 1 & 1 & 1 & 1 & 1 & 1 & 1 \\ 1 & 1 & 0 & 0 & 0 & 0 & 0 & 0 \\ 1 & 1 & 0 & 0 & 0 & 0 & 0 & 0 \\ 1 & 1 & 0 & 0 & 0 & 0 & 0 & 0 \\ 1 & 1 & 0 & 0 & 0 & 0 & 0 & 0 \\ 1 & 1 & 0 & 0 & 0 & 0 & 0 & 0 \\ 1 & 1 & 0 & 0 & 0 & 0 & 0 & 0 \end{bmatrix} \tag{1.9}$$

4. Modeling Fixed and More General Devices

In addition to reconfigurable devices many fixed routing devices can appear in a WSON. These include splitters, combiners, and Fixed Optical Add/Drop Multiplexers (FOADM). Although these are not under the control of the control plane their presence can affect or dictate the choice of paths used to reach a destination. We can model this fixed connectivity with a *fixed connectivity* matrix $\mathbf{F} = \{f_{ij}\}$ along with a set of fixed port wavelength constraints. For example the splitter, combiner and fixed demultiplexer of **Figure 8** can be specified by the following fixed connectivity matrices:

$$\mathbf{F}_a = [1 \quad 1 \quad 1],\ \mathbf{F}_b = \begin{bmatrix} 1 \\ 1 \\ 1 \end{bmatrix},\ \text{and}\ \mathbf{F}_c = [1 \quad 1 \quad \cdots \quad 1]. \tag{1.10}$$

To tell the difference between a splitter and a demultiplexer we note that the splitter doesn't have any port wavelength constraints while the demultiplexer will have a set of egress port wavelength constraints equivalent to equation (1.2).

A. Hybrid Modeling Example

Most fixed WSON subsystems would not participate in the control plane and their presence would be inferred, e.g., from constraints on a receiving end system. However, some reconfigurable subsystems are better modeled as a combination of reconfigurable and fixed subsystems. For example, a variant of a type II ROADM built from switching technology rather than a wave blocker that has additional constraints is shown in **Figure 9.** Here we assume that we have an ideal switching array of dimension M where $M < N$ and N is the number of WDM channels on the line. Hence we only have the capability to switch a subset of the wavelengths.

These types of ROADMs have been discussed in the literature [23,24]. The connectivity matrix will have the same structure as equation (1.1), but will now have dimensions $(M+1)\times(M+1)$. The port wavelength constraints for the drop ports E_j are:

$$\Lambda_j = \{\lambda_{N-M}, \lambda_{N-M+1}, ..., \lambda_N\} \tag{1.11}$$

and

$$\sum_k w_{jk} \le 1 \tag{1.12}$$

To be explicit in modeling the pass through behavior of wavelengths $\lambda_1, ..., \lambda_{N-M-1}$ we can model the *fixed* structure of **Figure 9** with

$$F = \begin{cases} f_{ij} = 1 & i = 1, j = M+1 \\ f_{ij} = 0 & \text{otherwise} \end{cases} \tag{1.13}$$

Along with the following *fixed* port constraint for E_{M+1}:

$$\Lambda_j = \{\lambda_1, \lambda_2, ..., \lambda_{N-M-1}\} \tag{1.14}$$

B. More General Modeling Example

We saw with the ROADM of **Figure 9** that a single switched connectivity matrix **C** along with port constraints wasn't sufficient to specify the behavior of the system. In this case we needed to supplement this information with the fixed connectivity matrix **F** and additional fixed port wavelength constraints. In the general case we have two ways to model switches with more complicated internal structure: (1) we can model the system as a collection of wavelength dependent connectivity matrices or (2) we model the system with a set of internal nodes along with *internal* link constraints.

In **Figure 10** (a) we show a WSON system with two ingress and two egress ports. It is represented internally by four switching nodes and four wavelength constrained links. The internal link from port I_1 to port E_2 only supports a single channel of wavelength λ_1 and the link from port I_2 to port E_1 only supports a single channel of wavelength λ_2. A model based on a single connection matrix **C,** equation (1.15), would not work since both egress ports support the wavelength set $\{\lambda_1, \lambda_2\}$ and hence there is no way to tell from this description that λ_2 from I_1 cannot be switched to port E_2.

$$\mathbf{C} = \begin{bmatrix} 1 & 1 \\ 1 & 1 \end{bmatrix} \tag{1.15}$$

An equivalent representation in terms of two separate switched connection matrices with their own sets of port wavelength constraints is possible. These can be derived from **Figure 10** (b) and (c) where we show the wavelength dependent connectivity of the system which would lead to the wavelength dependent switched connectivity matrices:

$$\mathbf{C}_{\lambda_1} = \begin{bmatrix} 1 & 1 \\ 0 & 1 \end{bmatrix} \text{ and } \mathbf{C}_{\lambda_2} = \begin{bmatrix} 1 & 0 \\ 1 & 1 \end{bmatrix}. \tag{1.16}$$

In general any WSON switching system without wavelength converters can be characterized by a set of wavelength dependent fixed and switched connectivity matrices which leads to the representation shown in **Figure 11** where each fixed and switched block has its own set of port/wavelength constraints.

C. Use in Path Computation

Given a general representation of a switch in terms of fixed and switched connectivity matrices and constraints how should we construct a model for use in a network graph? First of all an algorithm for solving the RWA problem will know how to deal with link constraints since these are always present in one form or another. Our interest here is what to substitute into the overall WSON network graph for the switching subsystem based on the **C** matrix.

The simplest approach to create a subgraph representing the connectivity of C is via a generic bipartite subgraph as shown in **Figure 12** (a). A bipartite graph is a graph whose set of nodes has been partitioned into two disjoint sets. Here we have added an internal node for each ingress and egress port and an internal link for each $c_{ik} = 1$. Hence the two sets of nodes of our bipartite graph correspond to the internal ingress and egress nodes respectively. In **Figure 12**(b) we show this generic realization approach applied to the **C** matrix of equation (1.1). Now since path computation algorithms scale in terms of the number of nodes and links, this particular graph representation can be quite wasteful of computing resources, since for our simple two degree, N-channel unidirectional ROADM we added $2(N+1)$ internal nodes and $2N+1$ internal links. In addition most of the added nodes and links can be seen to be superfluous or redundant.

5. Encoding and Representation

The connectivity matrix for ROADMs with a large number of add/drop as compared to line side ports will be sparse and hence standard sparse matrix techniques could be applied for efficient transmission. In the case of higher degree ROADMs such as those shown in section 3.D this would be less than optimal. First, some of the connectivity matrices, as we have seen, were not that sparse, and second, we are still left with the problem of finding an efficient graph representation for use in path computation.

One intuitively appealing approach to encoding the connectivity matrix is to break the switch down into the fewest largest non-blocking sub-switches possible. This corresponds to the problem of finding the minimum number of complete bipartite subgraphs that cover the corresponding bipartite graph of **Figure 12**(a). This is, in general, a computationally difficult problem which only has guaranteed fast solution for restrictive graph classes [25]. However one can take advantage of knowledge of the WSON switches functionality or start with an efficient algorithm to list maximal bipartite subgraphs [26].

A. Efficient Matrix Encoding

A general way to efficiently represent the switched or fixed connectivity matrix is by listing sets of ingress and egress ports that have full connectivity to each other. Let **I** represent the set of all ingress ports, and **E** the set of all egress ports. Denote by $\mathrm{I}_j \subset \mathrm{I}$ a specific subset of the ingress ports, and $\mathrm{E}_j \subset \mathrm{E}$ a specific subset of the egress ports. Now we can represent the matrix **C** via a complete bipartite cover, i.e., a collection of pairs of subsets of **I** and **E** with the requirement:

$$\left\{ \left(\mathrm{I}_j, \mathrm{E}_j \right) \mid i_p \in \mathrm{I}_j, e_q \in \mathrm{E}_j \Rightarrow c_{pq} = 1 \right\} \tag{1.17}$$

And

$$\bigcup_j \mathrm{I}_j = \mathbf{I}, \quad \bigcup_j \mathrm{E}_j = \mathbf{E} \tag{1.18}$$

Such a bipartite cover always exists, for example let $\mathrm{I}_j = \{I_j\}$ and the sets $\mathrm{E}_j = \{e_k \mid c_{jk} = 1\}$ and this is just a row compressed form for the matrix **C** and leads to the graph representation of **Figure 12**(a). By making the sets I_j and E_j "maximal" we can reveal more of the structure of the switch for use in the graph representation and save space when passing this information via a control plane. Although this is generally a hard problem, current WSON switching elements implemented and proposed exhibit a great deal of relatively straight forward structure in their connectivity (but not necessarily their internal design) making the job of finding maximal sets I_j and E_j relatively straight forward as illustrated in the following examples.

Example 1: The two degree ROADM of **Figure 2** can be represented by the following two pairs: $(\{I_1\},\{E_1,E_2,\ldots,E_{N+1}\})$ and $(\{I_2,I_3,\ldots,I_{N+1}\},\{E_{N+1}\})$.

Example 2: The per port add/drop higher degree ROADM of **Figure 6** can be represented by the following ingress/egress set pairs: $(\{I_1,I_2\},\{E_1,E_2\})$, $(\{I_1\},\{E_6,E_7,E_8\})$, $(\{I_2\},\{E_3,E_4,E_5\})$, $(\{I_3,I_4,I_5\},\{E_2\})$, and $(\{I_6,I_7,I_8\},\{E_1\})$.

Example 3: The per node add/drop higher degree ROADM of **Figure 7** can be represented by the pairs: $(\{I_1,I_2\},\{E_1,E_2,\ldots,E_8\})$ and $(\{I_3,I_4,\ldots,I_8\},\{E_1,E_2\})$.

B. Graph Representation

Given a compact representation, $(\mathrm{I}_j,\mathrm{E}_j)$ for the connectivity matrix **C** we can generate a compact graph representation for use in path computation as follows:

1. Let each $(\mathrm{I}_j,\mathrm{E}_j)$ define a non-blocking internal switching node.

2. If ingress port $i_k \in \mathrm{I}_j$ and $i_k \notin \mathrm{I}_p$ for all $p \neq j$ then we can directly attach this ingress port to this switching block.

3. If egress port $e_k \in \mathrm{E}_j$ and $e_k \notin \mathrm{E}_p$ for all $p \neq j$ then we can directly attach this egress port to this switching block.

4. If ingress port $i_k \in \mathrm{I}_j$ for more than one value of *j* then we insert a node with i_k as ingress and with egress links to all other blocks such that $i_k \in \mathrm{I}_j$.

5. If egress port $e_k \in \mathrm{E}_j$ for more than one value of *j* then we insert a node with e_k as egress and with ingress links from all other blocks such that $e_k \in \mathrm{E}_j$.

6. Merging: internal nodes with only one egress or ingress link can be merged with their adjacent node.

Example 4: Given the compact encoding from Example 1. We create two switching blocks (**Figure 13**a). We see that E_{N+1} is a common egress port to both blocks and add a node with E_{N+1} as egress and connect both these blocks to this node (**Figure 13**b). Finally, we merge nodes where possible (**Figure 13**c).

The easy conversion from this compact encoding to a minimal graph representation is a feature of our WSON switching system model and differs in a key way from that previously used in Generalized Multi-Protocol Label Switching (GMPLS) routing [3]. In current GMPLS routing information is currently associated with individual links in a switching subsystem which would be fine for a row compressed encoding of the connectivity matrix, but if such a mechanism was used then we have to solve the graph representation problem again. Hence for WSON switching systems it would be better to introduce the compact encoding of the connectivity matrix as a new node wide attribute.

6. Conclusion

The need for and the requirements for a simplified Switch model for asymmetric WSON switching systems for use in GMPLS standards and automated path computation was given. This model consists of possibly multiple fixed and switched connectivity matrices along with associated port wavelength constraints. Both the connectivity matrices and the port wavelength constraints can be compactly represented and this was demonstrated for a number of common WSON switch types. Furthermore the compact representation given for the connectivity matrices leads to a minimal graph representation for use in path computation. This model and its encodings have been adopted for use in emerging WSON control plane standards [8-10].

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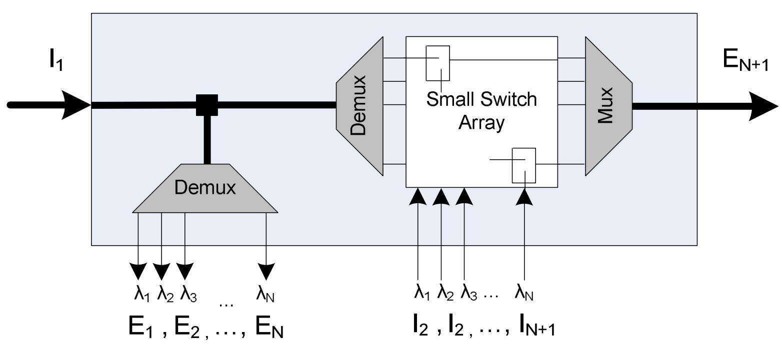

Figure 1. One *implementation of a type I ROADM*.

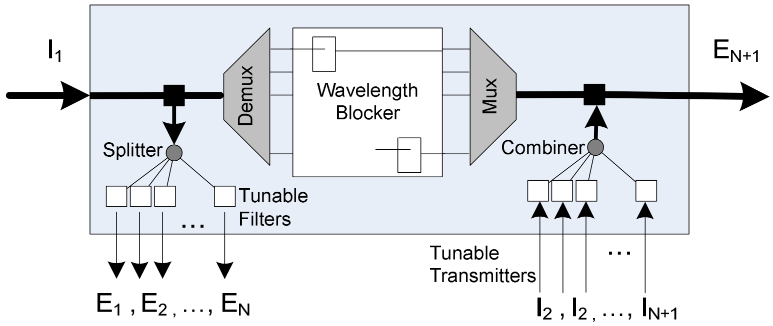

Figure 2. *A possible implementation of a type II ROADM.*

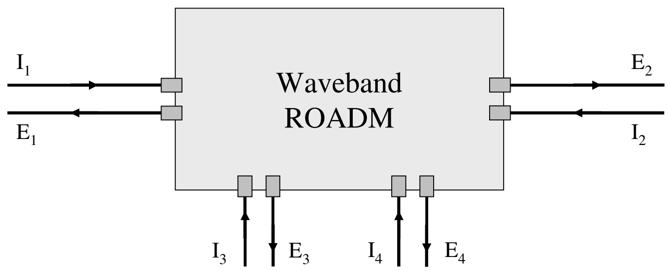

Figure 3: ROADM with waveband add/drop ports

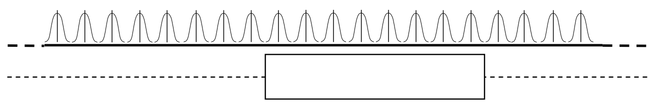

Figure 4: Initial state of the waveband drop port. The window indicates that the waveband has not been anchored prior to the first wavelength allocation. The white color of the window indicates that no wavelengths have been allocated.

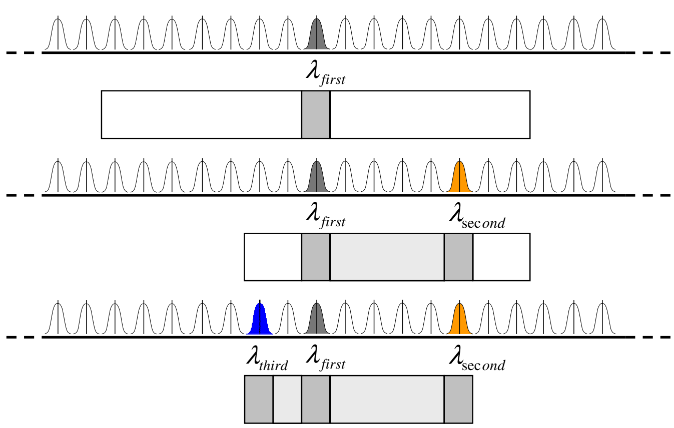

Figure 5: The figure shows allocated and available wavelengths, and the waveband tuning constraint after the first, second, and third wavelength has been allocated. The meanings of the

colors are; available (white), dropped but available (lighter grey), i.e. reserved, and allocated (darker grey). In this example the width of the waveband is 8 channels.

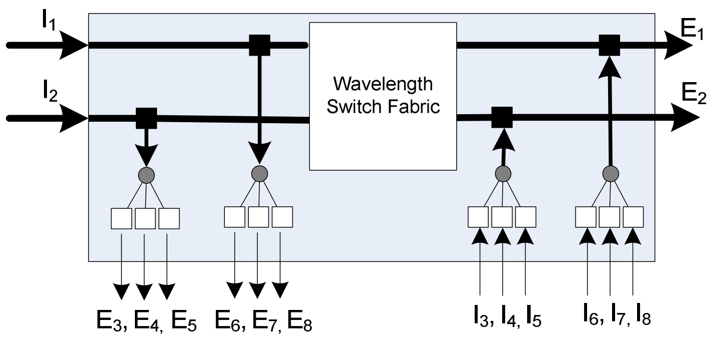

Figure 6. A higher degree ROADM with per port add/drop.

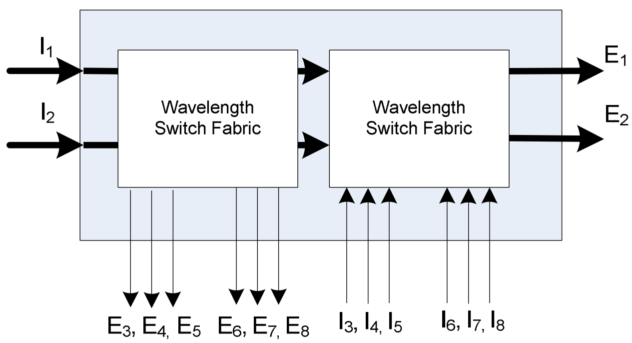

Figure 7. A higher degree ROADM with per node add/drop

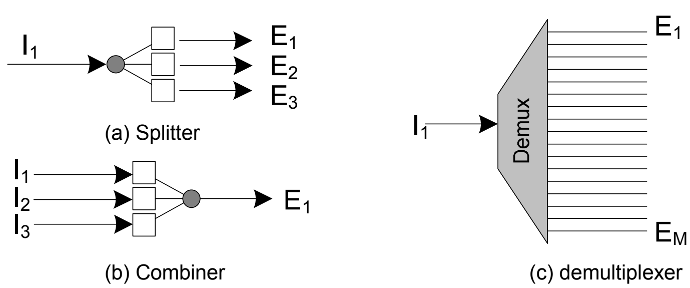

Figure 8. Examples of common fixed WSON subsystems.

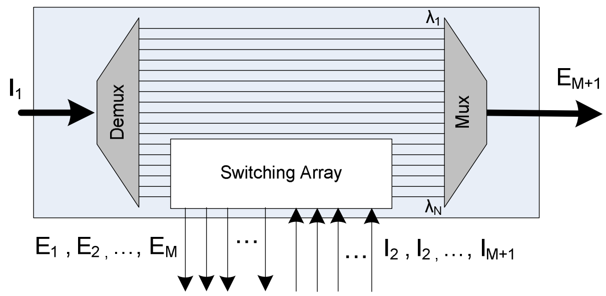

Figure 9. A type II ROADM with additional constraints.

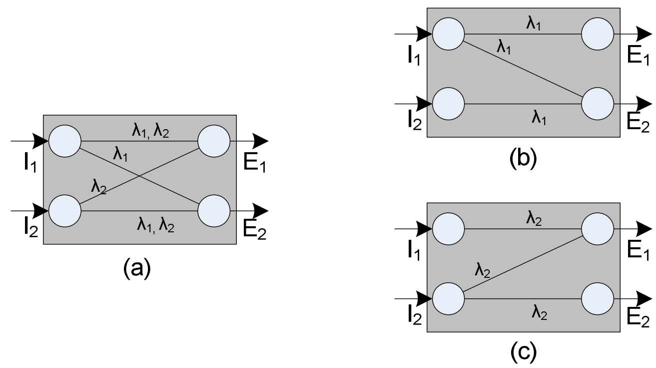

Figure 10 (a) System, (b) λ_1 connectivity, and (c) λ_2 connectivity.

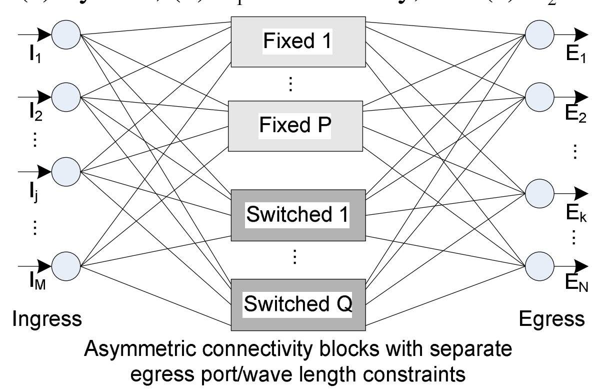

Figure 11. General representation of a WSON switch without wavelength converters.

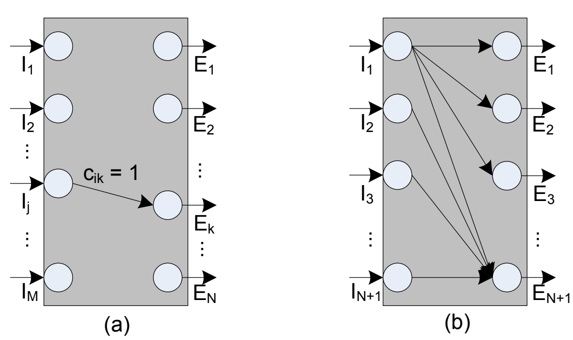

Figure 12 (a) General realization, (b) Generic realization for the **C** matrix of equation (1.1).

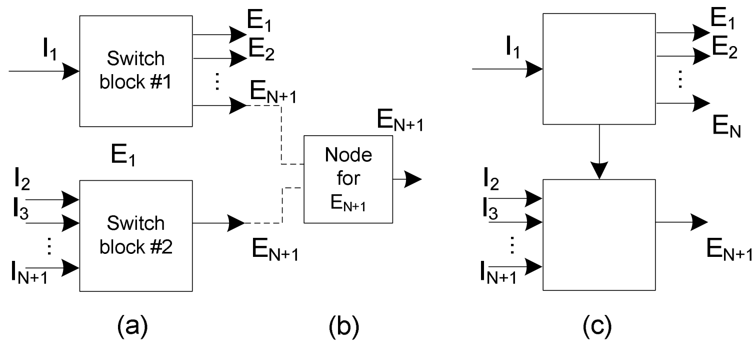

Figure 13. Reduced graph representation for our 2-degree ROADM example.