A WSON GMPLS Model for Signal Compatibility and Switching Systems including Wavelength Converters and Regenerators

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Abstract—**Various wavelength switched optical network (WSON) switching systems may include wavelength conversion and regeneration functionality. These are important to model from an optical path computation perspective for a number of reasons. First, the presence of wavelength converters at a node can ease the wavelength continuity constraint. Second the availability of regenerators can reduce optical impairment related constraints. Finally, since wavelength conversion and regeneration are typically implemented via optical-electronic techniques one must insure that the optical signals are compatible with the optical-electronic processing used along the signal path. This document provides an information model and efficient coding for use in GMPLS to represent these potentially limited processing resources, their constraints, and their capabilities. Note that translucent networks are a subset of the optical networks containing such network elements.**

Index Terms—**optical networks, control plane, GMPLS, switch models, ROADMs, wavelength converters, signal compatibility, translucent networks.**

I. Introduction

Wavelength converters can play a key role in reducing blocking in WSONs. Regenerators similarly reduce blocking by providing additional (longer) paths that a signal can take when traversing a WSON. To enable routing and wavelength assignment (RWA) algorithms (path computation) to take into account the availability of wavelength converters and regenerators they need to know the following:

- The nodes that support wavelength conversion or regeneration.
- The accessibility of the wavelength conversion or regeneration pool from a particular ingress/egress port pair and wavelength for a particular node.
- Limitations on the types of signals that can be wavelength converted or regenerated.

In an earlier paper [Switch] we showed how to model a general WSON switch for control plane purposes in terms of parallel fixed and switched connectivity blocks as shown in Figure 1 and such a model is currently the baseline CCAMP optical switch/ROADM model. The "fixed" block implies that there is no choice in connectivity. We can also use this to model fixed multi-cast connectivity such as splitters and combiners. The switching block, on the other hand, only describes potential unicast connectivity, that is cross connects that could be realized but do not necessarily have to be made. In Figure 2 we show a compatible generalization of the previous WSON switching system model to include a fairly general subsystem block labeled resources which can include wavelength conversion, regeneration, performance monitors, or other processing resources. One important difference between the blocks in Figure 2 is that as part of our previous model we do not keep any state information about the *fixed* or *switched* blocks. This was for two reasons: (1) to simplify the model, (2) switch internals tend to be vendor proprietary and hence would typically not be published. For the *resource* block in Figure 2 we may need to keep track of scarce processing resources and hence may need to keep some kind of limited state information for the *resource* block.

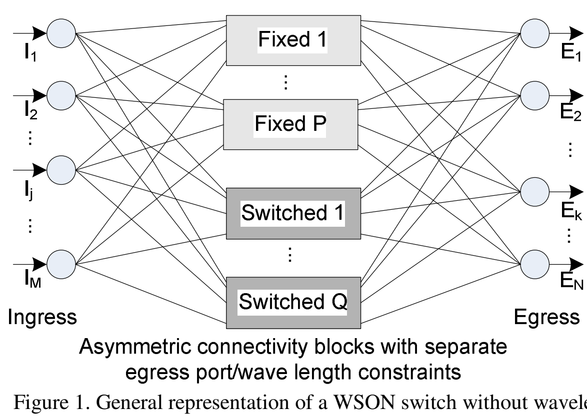

Figure 1. General representation of a WSON switch without wavelength converters.

The fixed and switched asymmetric connectivity blocks are specified by fairly straightforward fixed and switched connectivity matrices along with the fixed and switched port-wavelength constraints. Our goal in this work is to come up with a reasonable fidelity model for the resources block for use with the control plane.

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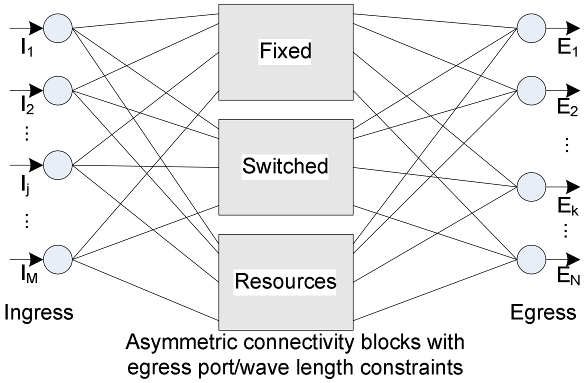

Figure 2. Extended model for a WSON switching subsystem to include wavelength conversion.

In the following we first give a moderately general model for processing resources within a DWDM network element.
We will show how well we can use this model to represent the resource pools in a variety of switch architectures, model OEO switches with DWDM optics, and regenerator banks with tunable lasers (able to act as wavelength converters). We also look at a recently published wavelength convertible switch architecture whose full description would require additional state. In addition, the examples will show how this representation hides system implementation specifics.

II. Model and Application

Our fairly general representation for the converter block is shown in Figure 4. This representation allows for limited connectivity between the various ingress ports and resource blocks and for limited connectivity between the resource blocks and the egress ports. The resource blocks can be individual resources such as wavelength converters as shown in Figure 4. However a representation that allows for blocks of "indistinguishable" resources can greatly enhance the encoding efficiency for the model.

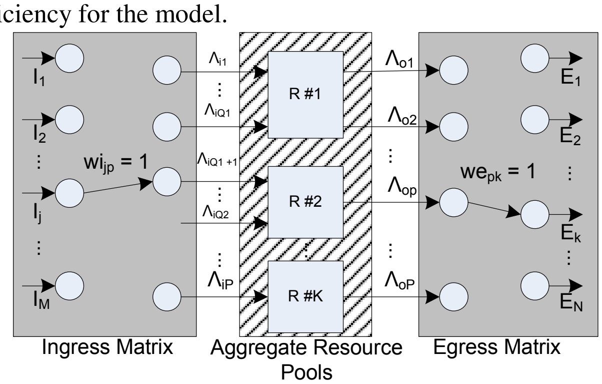

Figure 3. *General representation of processing resources in aggregate pools (individual resources within an aggregate are indistinguishable).*

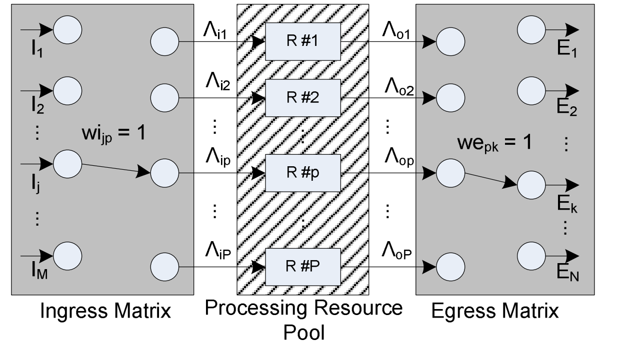

Figure 4. General representation of processing resources subsystem within a WSON switching system (fine grained resource accounting).

On the input of the resource pool we can have input port wavelength restrictions. These can be simple range, restrictions or fairly complicated sets as we will see in the examples. Similarly we allow for port-wavelength restrictions on the egress side of the resource pool. Since we will be restricting our discussion to resources that process only a single input wavelength to produce a single output wavelength, we have a single wavelength restriction on the input to all resources.
This leads to the following model the connectivity and usage state using the following:

Let $\mathbf{RI} = \{ri_{ip}\}$ denote the *processing resource ingress connectivity matrix* which indicates either *fixed* (multi-cast) connectivity or switched uni-cast connectivity, i.e., whether a wavelength on ingress port I_i is (can be) connected to resource block R_p, i.e., $ri_{ip} = 0 \text{ or } 1$. We will denote the fixed and switched cases by $\mathbf{RI}_F$ and $\mathbf{RI}_S$ respectively.

Let $\Lambda_{i,p} = \{\lambda_k | \lambda_k \text{ can enter resource } p\}$ denote the ingress wavelength constraint for resource block *p*.

Let $\Lambda_{o,p} = \{\lambda_k | \lambda_k \text{ can exit resource } p\}$ denote the egress wavelength constraint for resource block *p*.

Let $\mathbf{RE} = \{re_{pk}\}$ denote the *processing resource egress connectivity matrix* which indicates either *fixed* (multi-cast) connectivity or *switched* uni-cast connectivity, i.e., whether a resource block R_p is (can be) connected to egress port E_k, i.e., $re_{pk} = 0 \text{ or } 1$.

Let $\mathbf{RS} = \{rs_j\}$ be the resource block usage state, where rs_j is the number of resources in the block that are currently in use.
Of all these definitions the intent is that only RS is dynamic.

One of the benefits of this model is that one can readily answer the question of whether a resource is available between a particular ingress and egress port that can process a particular incoming wavelength to a particular outgoing wavelength.

III. Switch Architectures and Modeling

WSON switches incorporating wavelength converters are sometimes referred to as wavelength convertible switches [1] or wavelength convertible routers [2]. These switches come in a variety of architectures that permit more or less cost effective implementations depending on the optical switching technologies employed. The purpose here is not to judge any particular switch architecture but to review those that have been proposed to see their complexity from a modeling point of view.
The following examples feature a variety of optical components some such as WDM multiplexers and demultiplexers are wavelength dependent on their ingress and egress respectively, others such as splitters or combiners are not wavelength dependent.

A. Shared per Node

The Shared per node (SPN) architecture [3], [4] features a pool of wavelength converter shared on a per switch basis. An example block diagram for a four port switch in a four channel system with a two wavelength converter pool is shown in Figure 5.

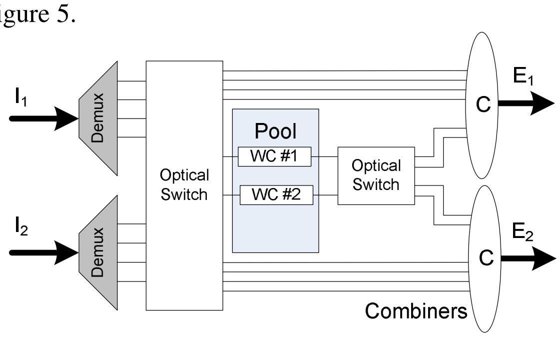

Figure 5. Block diagram of an example shared per node architecture.

In the ideal shared per node design every input fiber and wavelength can reach any wavelength converter and every wavelength converter can reach any egress port. In this case the wavelength converters in the pool are indistinguishable and hence can be grouped into a single aggregate. It can be readily model as follows:

$$RI_S = [1], \quad RE_S = [1] \tag{1.1}$$

$$\Lambda_i = \{\lambda_1, \lambda_2, \lambda_3, \lambda_4\} = \Lambda_o \tag{1.2}$$

and

$$RS = [n] \text{ where } n = 0,1, \text{ or, } 2 \tag{1.3}$$

B. Shared per Link

The Shared per link architecture [4], also known as Shared per Fiber (SPF) and Shared per Output Fiber (SPOF) [3] features a pool of wavelength converters on each egress link that can be shared only by signals on that link. A block diagram of an example of a four port switch in a four channel system with four wavelength converters in its pool is given in Figure 6.

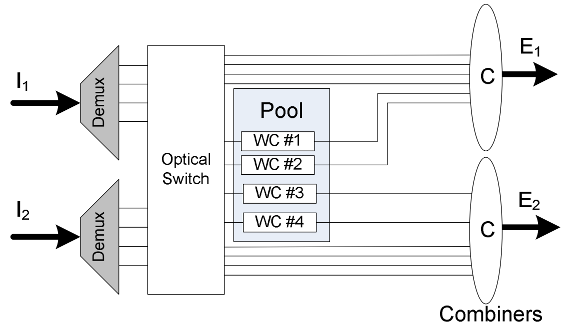

Figure 6. Low channel count shared per link example.

A key difference between Figure 5 and Figure 6, besides the number of wavelength converters, is the lack of a switching block from the wavelength converters to the ports. The converters for each link are indistinguishable so we can group the converters on a per link basis (two converter blocks). We can represent this with our model as follows:

$$RI_S = \begin{bmatrix} 1 & 1 \\ 1 & 1 \end{bmatrix}, \quad RE_S = \begin{bmatrix} 1 & 0 \\ 0 & 1 \end{bmatrix} \tag{1.4}$$

$$\Lambda_{i,p} = \{\lambda_1, \lambda_2, \lambda_3, \lambda_4\} = \Lambda_{o,p} \quad \text{for } p = 1 \text{ to } 4 \tag{1.5}$$

and

$$RS = \begin{bmatrix} rs_1 \\ rs_2 \end{bmatrix} \tag{1.6}$$

where $rs_1, rs_2 = 0,1, \text{ or } 2$.

C. Half-Clear Wavelength

The Half-Clear architecture of reference [4] , takes advantage that not all wavelength would necessarily need to be converter. We show an example of a Half-Clear four port switch with two shared wavelength converters in a four channel system in Figure 7, half the wavelengths entering the switch cannot reach the converters and the other half must go through the converter pool before leaving the switch.

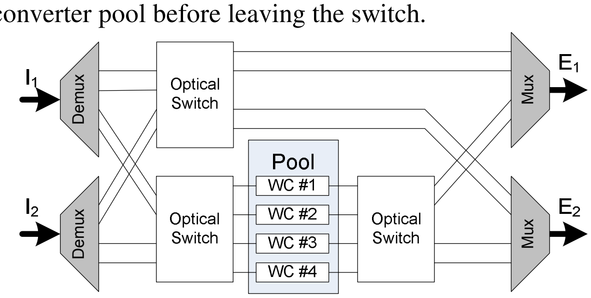

Figure 7. *Simple Half-Clear switch example***.**

One again all the wavelength converters in the pool are indistinguishable and hence we can group them into a single block. This architecture has simple ingress and egress connectivity to the pool and can be represented by

$$RI_S = [1], \quad RE_S = [1] \tag{1.7}$$

In this case only half the wavelength can reach the converters and we represent this by the wavelength converter ingress wavelength constraints:

$$\Lambda_i = \{\lambda_3, \lambda_4\} \tag{1.8}$$

The output wavelength constraints represent the wavelength selective nature of the WDM multiplexers used in the system:

$$\Lambda_o = \{\lambda_3, \lambda_4\} \tag{1.9}$$

Note that we still must insure that wavelength do not collide on any output fiber. We can use a wavelength converter usage state vector as in equation (1.6). However in this case we have only two input ports and two acceptable input wavelengths for all the converters which leads to potentially four wavelength that could possibly need to be converted and since we have four converters there is no need to keep track of the state.

D. Shared by Wavelength

The Shared-by-wavelength [5] is a recent general switch architecture that aims to reduce the size of the optical switches utilized. The design can be characterized by four numbers *W*, *M, q,* and *p* where *W* is the number of channels on the WDM links, *M* is the total number of converters, *q* is the maximum number of signals of a particular wavelength that can reach the converter pool, and *p* is the maximum number of signals at a particular wavelength that can leave the converter pool. The general layout is shown in **Figure 8** with reference [5] providing specific interconnectivity details for specific design parameters.

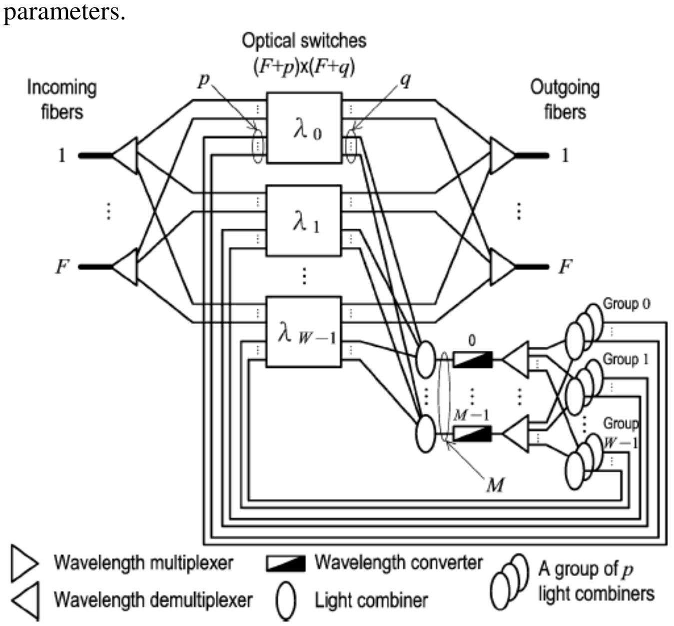

Figure 8. *The shared by wavelength architecture from* **[5]**.

In our analysis we are only interested in the restrictions what ports and or wavelengths can reach the converters and what wavelengths can egress a converter to reach a specific port. For concreteness we look at a switch with four ingress and four egress fibers, all fibers supporting 5 channels, three shared wavelength converters and the design parameters q=2 and p =2. In Figure 9 we show the structure leading to the wavelength converters. In this architecture every input port can reach every wavelength converter in the pool so we have

$$RI_S = \begin{bmatrix} 1 & 1 & 1 \\ 1 & 1 & 1 \\ 1 & 1 & 1 \\ 1 & 1 & 1 \end{bmatrix} \tag{1.10}$$

However due to the limited size of the switches connecting to the converters via the combiners we have the following ingress port wavelength restrictions

$$\begin{aligned} \Lambda_{i,1} &= \{\lambda_1, \lambda_2, \lambda_4, \lambda_5\} \\ \Lambda_{i,2} &= \{\lambda_1, \lambda_3, \lambda_4\} \\ \Lambda_{i,3} &= \{\lambda_2, \lambda_3, \lambda_5\} \end{aligned} \tag{1.11}$$

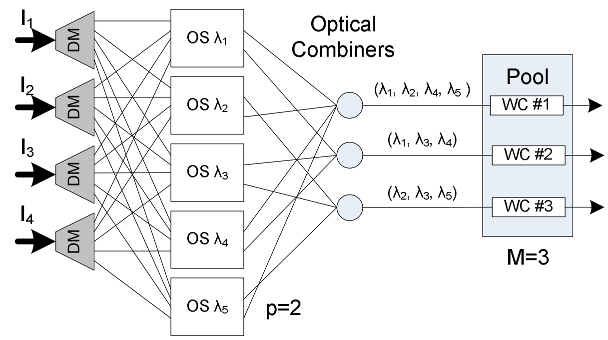

Figure 9. *Ingress section for shared by wavelength with W=5, M=3, and p=2.*

In Figure 10 we show the egress section from the pool to the output fibers for our shared-by-wavelength example. Here we see that any wavelength from any of the converters can *potentially* reach any output fiber so we have

$$RE_S = \begin{bmatrix} 1 & 1 & 1 & 1 \\ 1 & 1 & 1 & 1 \\ 1 & 1 & 1 & 1 \end{bmatrix} \tag{1.12}$$

and

$$\Lambda_{o,p} = \{\lambda_1, \lambda_2, \lambda_3, \lambda_4, \lambda_5\} \quad \text{for } p = 1 \text{ to } 3. \tag{1.13}$$

However this architecture has additional state dependent blocking not captured by our model. In particular, we see in Figure 10 that the use of combiners prior to the wavelength switches implies that no more that q=2 wavelength converters can output signals at the same wavelength regardless of what port they are intended. In fact the situation is a bit worse, by looking at Figure 10 we see the following additional constraint that WC#1 and WC#3 cannot both convert the same lambda at the same time.

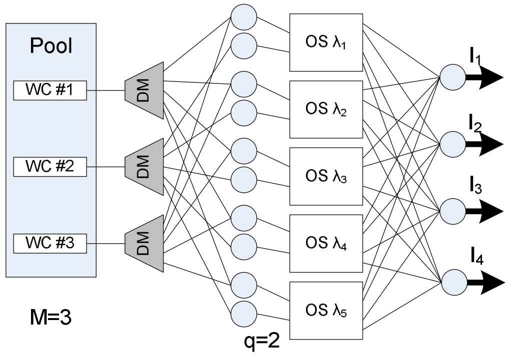

Figure 10. *Egress section for shared by wavelength with W=5, M=3, and q=2.*

To model such a situation requires one or more of the following (1) more internal switch/converter pool implementation details, (2) additional state, or (3) additional constraints. From a control plane standardization point item (1) is the least desirable since vendors don't like to disclose design information and standards aim to be general. Additional state is of concern if it grows too large, in addition we need to specify how to use this state to assess the availability of a converter between two ports and wavelengths. Additional constraints are most likely the easiest and most compact. We saw in the previous example the simple additional constraint that not more than p=2 wavelength converters can convert to the same wavelength.

Note that a "complete" switch model is not necessary for GMPLS routing since the final determination of whether a processing resource is available will be determined when we attempt to set up a connection via GMPLS signaling. Better modeling of resources helps reduce the probability of blocking due to unavailable switch resources but cannot eliminate it [6].

E. Share-with-Local

The Share-with-local approach [4] can be thought of as less of a specific architecture but rather an engineering approach to add wavelength converters to existing subsystems such as ROADMs.

In Figure 11 we show a colored two degree ROADM with an external converter pool attached, and in Figure 12 we show an alternative implementation based on an electronic switch and tunable lasers. Both systems yield the same model which illustrates how the model can hide implementation specific details. The resulting system has six ingress ports and six egress ports. In both cases the wavelength converters are indistinguishable from each other and hence can be modeled by a single resource block.

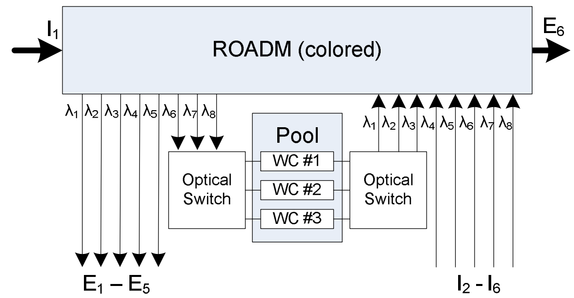

Figure 11. *Colored ROADM with external converter pool.*

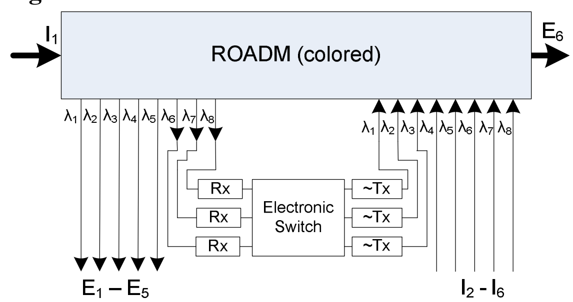

Figure 12. *Colored ROADM with receivers, electronic switch and tunable lasers.*

The add ports (I2-I6) cannot reach the wavelength converter pool or electronic switch so we have

$$RI_S = \begin{bmatrix} 1 \\ 0 \\ 0 \\ 0 \\ 0 \\ 0 \end{bmatrix} \tag{1.14}$$

In addition the wavelength converters or electronic switch outputs cannot reach the drop ports which gives:

$$RE_S = \begin{bmatrix} 0 & 0 & 0 & 0 & 0 & 1 \end{bmatrix} \tag{1.15}$$

The ingress wavelength constraints to the converter pool or electronic switch are:

$$\Lambda_i = \{\lambda_6, \lambda_7, \lambda_8\} \tag{1.16}$$

The egress wavelength constraints from the converter pool or electronic switch are:

$$\Lambda_o = \{\lambda_1, \lambda_2, \lambda_3\} \tag{1.17}$$

Note that in this case we can summarize the state of the converter pool via the total number of converters and the total number available $RS = [n]$ where $n = 0, \ldots, 3$

In Figure 13 we show a colorless ROADM connected to a set of wavelength converter. By "colorless" we mean that any wavelength can exit or ingress at any port subject to wavelength collision constraints.

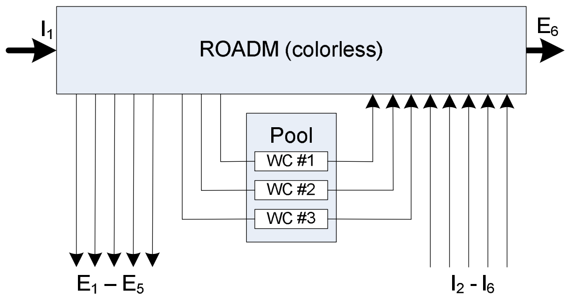

Figure 13. *Colorless ROADM with external converter pool.* As in the colored ROADM case we have the RI and RE matrices of equations (1.14) and (1.15), however in this case we have much more flexibility in conversions since

$$\Lambda_i = \{\lambda_1, \lambda_2, \lambda_3, \lambda_4, \lambda_5, \lambda_6, \lambda_7, \lambda_8\} = \Lambda_o \quad (1.18)$$

Note that this case is very similar to the share by node case.

F. DWDM Optics for an Electro-Optical Switch

Here we look at an electronic switch fabric surrounded by DWDM optics.

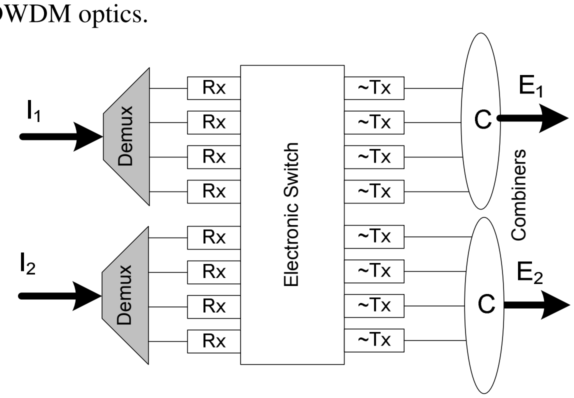

Figure 14. *DWDM demultiplexers connected to an electronic switch fabric with tunable lasers feeding combiners.*

Note that there is no choice as to whether a signal goes through the electronic switch, i.e., all ports are connected to the "resource block". Assuming a non-blocking electronic fabric then any wavelength on any input port can get to any output port and be converted to any wavelength in the range of the transmitter and not already used on that output port. Hence we can model this as:

$$RI_F = [1], \quad RE_S = [1]$$

With essentially no extra input or output wavelength constraints.

G. Fixed Regenerator Bank

Now consider a simplified regenerator bank with wavelength conversion capabilities as show in Figure 15.

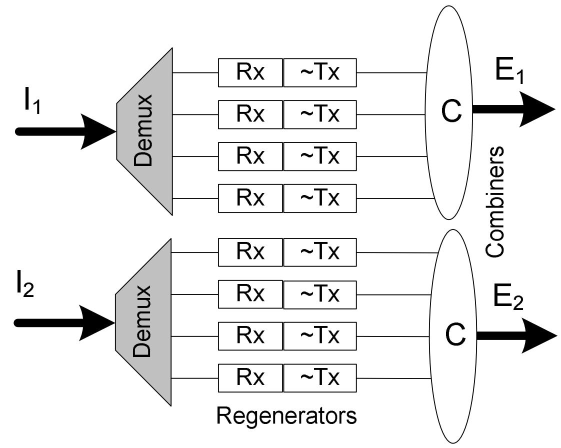

Figure 15. *Regeneration bank with tunable transmitters.*

The regenerators/tunable lasers for each port are indistinguishable so we can group them into blocks on a per port basis. Ingress I1 can reach one set of converters, and ingress I2 can reach another set. Similarly those disjoint sets of converters can only reach either egress E1 or egress E2 but not both. We can represent each of these "sets of converters" by a single column/row in the RI, and RE connectivity matrices. These blocks represent fixed connectivity (not potential connectivity).

$$RI_F = \begin{bmatrix} 1 & 0 \\ 0 & 1 \end{bmatrix}, \quad RE_F = \begin{bmatrix} 1 & 0 \\ 0 & 1 \end{bmatrix}$$

Since there is no contention for wavelength resources we don't need to keep pool state and hence don't need to identify individual resources (converters/regenerators).

IV. Signal Compatibility Modeling

Now we should be able to apply the compatibility constraint stuff to the "processing blocks". This even makes sense in the case of the OEO switch of Figure 14 since this is acting as a WSON network element and not a network element in a SONET/SDH network.

V. Efficient Encoding

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VI. Conclusion

References

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