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# Framework for GMPLS and PCE Control of Wavelength Switched Optical Networks (WSON)

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Status of this Memo

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Abstract

This memo provides a framework for applying Generalized Multi-Protocol Label Switching (GMPLS) and the Path Computation Element (PCE) architecture to the control of wavelength switched optical networks (WSON). In particular we provide control plane models for key wavelength switched optical network subsystems and processes. The subsystems include wavelength division multiplexed links, tunable laser transmitters, reconfigurable optical add/drop multiplexers (ROADM) and wavelength converters.

Lightpath provisioning, in general, requires the routing and wavelength assignment (RWA) process. This process is reviewed and the information requirements, both static and dynamic for this process are presented, along with alternative implementation scenarios that could be realized via GMPLS/PCE and/or extended GMPLS/PCE protocols. This memo does NOT address optical impairments in any depth and focuses on topological elements and path selection constraints that are common across different WSON environments. It is expected that a variety of different techniques will be applied to optical impairments depending on the type of WSON, such as access, metro or long haul.

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## 1. Introduction

From its beginning Generalized Multi-Protocol Label Switching (GMPLS) was intended to control wavelength switched optical networks (WSON) with the GMPLS architecture document [RFC3945] explicitly mentioning both wavelength and waveband switching and equating wavelengths (lambdas) with GMPLS labels. In addition a discussion of optical impairments and other constraints on optical routing can be found in [RFC4054]. However, optical technologies have advanced in ways that make them significantly different from other circuit switched technologies such as Time Division Multiplexing (TDM). Service providers have already deployed many of these new optical technologies such as ROADMs and tunable lasers and desire the same

automation and restoration capabilities that GMPLS has provided to TDM and packet switched networks. Another important application of an automated control plane such as GMPLS is the possibility to improve, via recovery schemes, the availability of the network.  One of the key points of GMPLS based recovery schemes is the capability to survive multiple failures while legacy protection mechanism such as 1+1 path protection can survive from a single failure.  Moreover this improved availability can be obtained using less network resources.

This document will focus on the unique properties of links, switches and path selection constraints that occur in WSONs.  Different WSONs such as access, metro and long haul may apply different techniques for dealing with optical impairments hence this document will NOT address optical impairments in any depth, but instead focus on properties that are common across a variety of WSONs.

This memo provides a framework for applying GMPLS and the Path Computation Element (PCE) architecture to the control of WSONs.  In particular we provide control plane models for key wavelength switched optical network subsystems and processes. The subsystems include wavelength division multiplexed links, tunable laser transmitters, reconfigurable optical add/drop multiplexers (ROADM) and wavelength converters.

Lightpath provisioning, in general, requires the routing and wavelength assignment (RWA) process. This process is reviewed and the information requirements, both static and dynamic for this process are presented, along with alternative implementation architectures that could be realized via various combinations of extended GMPLS and PCE protocols.

## 2. Terminology

CWDM: Coarse Wavelength Division Multiplexing.

DWDM: Dense Wavelength Division Multiplexing.

FOADM: Fixed Optical Add/Drop Multiplexer.

OXC: Optical cross connect. A symmetric optical switching element in which a signal on any ingress port can reach any egress port.

ROADM: Reconfigurable Optical Add/Drop Multiplexer. An asymmetric wavelength selective switching element featuring ingress and egress line side ports as well as add/drop side ports.

RWA: Routing and Wavelength Assignment.

Wavelength Conversion/Converters: The process of converting an information bearing optical signal centered at a given wavelength to one with "equivalent" content centered at a different wavelength. Wavelength conversion can be implemented via an optical-electronic-optical (OEO) process or via a strictly optical process.

WDM: Wavelength Division Multiplexing.

Wavelength Switched Optical Networks (WSON): WDM based optical networks in which switching is performed selectively based on the center wavelength of an optical signal.

## 3. Wavelength Switched Optical Networks

WSONs come in a variety of shapes and sizes from continent spanning long haul networks, to metropolitan networks, to residential access networks. In all these cases we are concerned with those properties that constrain the choice of wavelengths that can be used, i.e., restrict the wavelength label set, impact the path selection process, and limit the topological connectivity. In the following we examine and model some major subsystems of a WSON with an emphasis on those aspects that are of relevance to the control plane. In particular we look at WDM links, Optical Transmitters, ROADMs, and Wavelength Converters.

### 3.1. WDM and CWDM Links

WDM and CWDM links run over optical fibers, and optical fibers come in a wide range of types that tend to be optimized for various applications from access networks, metro, long haul, and submarine links to name a few. ITU-T and IEC standards exist for various types of fibers. For the purposes here we are concerned only with single mode fibers (SMF). The following SMF fiber types are typically encountered in optical networks:

| ITU-T Standard | Common Name |
|---|---|
| G.652 [G.652] | Standard SMF |
| G.653 [G.653] | Dispersion shifted SMF |
| G.654 [G.654] | Cut-off shifted SMF |
| G.655 [G.655] | Non-zero dispersion shifted SMF |
| G.656 [G.656] | Wideband non-zero dispersion shifted SMF |

These fiber types are differentiated by their optical impairment characteristics such as attenuation, chromatic dispersion, polarization mode dispersion, four wave mixing, etc. Since these effects can be dependent upon wavelength, channel spacing and input

power level, the net effect for our modeling purposes here is to restrict the range of wavelengths that can be used.

Typically WDM links operate in one or more of the approximately defined optical bands [G.Sup39]:

| Band | Range (nm) | Common Name | Raw Bandwidth (THz) |
|---|---|---|---|
| O-band | 1260-1360 | Original | 17.5 |
| E-band | 1360-1460 | Extended | 15.1 |
| S-band | 1460-1530 | Short | 9.4 |
| C-band | 1530-1565 | Conventional | 4.4 |
| L-band | 1565-1625 | Long | 7.1 |
| U-band | 1625-1675 | Ultra-long | 5.5 |

Not all of a band may be usable, for example in many fibers that support E-band there is significant attenuation due to a water absorption peak at 1383nm. Hence we can have a discontinuous acceptable wavelength range for a particular link. Also some systems will utilize more than one band. This is particularly true for coarse WDM (CWDM) systems.

[Editor's note: the previous text is primarily tutorial in nature and maybe deleted or moved to an appendix in a future draft]

Current technology breaks up the bandwidth capacity of fibers into distinct channels based on either wavelength or frequency. There are two standards covering wavelengths and channel spacing. ITU-T recommendation [G.694.1] describes a DWDM grid defined in terms of frequency grids of 12.5GHz, 25GHz, 50GHz, 100GHz, and other multiples of 100GHz around a 193.1THz center frequency. At the narrowest channel spacing this provides less than 4800 channels across the O through U bands. ITU-T recommendation [G.694.2] describes a CWDM grid define in terms of wavelength increments of 20nm running from 1271nm to 1611nm for 18 or so channels. The number of channels is significantly smaller than the 32 bit GMPLS label space allocated to lambda switching.  A fixed mapping between the GMPLS label space and these ITU-T WDM grids as proposed in [Otani] would not only allow a common vocabulary to be used in signaling lightpaths but also in describing WDM links, ROADM ports, and wavelength converters for the purposes path selection.

With a tremendous existing base of fiber many WDM links are designed to take advantage of particular fiber characteristics or to try to avoid undesirable properties.  For example dispersion shifted SMF [G.653] was originally designed for good long distance performance in single channel systems, however putting WDM over this type of fiber

requires much system engineering and a fairly limited range of wavelengths. Hence for our basic, impairment unaware, modeling of a WDM link we will need the following information:

- Wavelength range(s): Given a mapping between labels and the ITU-T grids each range could be expressed in terms of a doublet (lambda1, lambda2) or (freq1, freq1) where the lambdas or frequencies can be represented by 32 bit integers.

- Channel spacing: currently there are about five channel spacings used in DWDM systems 12.5GHz to 200GHz and one defined CWDM spacing.

For a particular link this information is relatively static, i.e., changes to these properties generally require hardware upgrades. Such information could be used locally during wavelength assignment via signaling, similar to label restrictions in MPLS or used by a PCE in solving the combined routing and wavelength assignment problem.

## 3.2. Optical Transmitters

### 3.2.1. Lasers

WDM optical systems make use of laser transmitters utilizing different wavelengths (frequencies). Some laser transmitters were and are manufactured for a specific wavelength of operation, that is, the manufactured frequency cannot be changed. First introduced to reduce inventory costs, tunable optical laser transmitters are becoming widely deployed in some systems [Coldren04], [Buus06]. This allows flexibility in the wavelength used for optical transmission and aids in the control of path selection.

Fundamental modeling parameters from the control plane perspective optical transmitters are:

- Tunable: Is this transmitter tunable or fixed.

- Tuning range: This is the frequency or wavelength range over which the laser can be tuned. With the fixed mapping of labels to lambda's of [Otani] this can be expressed as a doublet (lambda1, lambda2) or (freq1, freq2) where lambda1 and lambda2 or freq1 and freq2 are the labels representing the lower and upper bounds in wavelength or frequency.

- o Tuning time: Tuning times highly depend on the technology used. Thermal drift based tuning may take seconds to stabilize, whilst electronic tuning might provide sub-ms tuning times. Depending on the application this might be critical. For example, thermal drift might not be applicable for fast protection applications.

- o Spectral Characteristics and stability: The spectral shape of the laser's emissions and its frequency stability put limits on various properties of the overall WDM system. One relatively easy to characterize constraint is the finest channel spacing on which the transmitter can be used.

Note that ITU-T recommendations specify many other aspects of a laser's such as spectral characteristics and stability. Many of these parameters are key in designing WDM subsystems consisting of transmitters, WDM links and receivers however they do not furnish additional information that will influence label switched path (LSP) provisioning in a properly designed system.

Also note that lasers transmitters as a component can degrade and fail over time. This presents the possibility of the failure of a LSP (lightpath) without either a node or link failure. Hence, additional mechanisms may be necessary to detect and differentiate this failure from the others, e.g., one doesn't not want to initiate mesh restoration if the source transmitter has failed, since the laser transmitter will still be failed on the alternate optical path.

### 3.2.2. Spectral Characteristics & Modulation Type

Contrary to some marketing claims optical systems are not truly "transparent" to the content of the signals that they carry. Each lightpath will have spectral characteristics based on its content, and the spacing of wavelengths in a WDM link will ultimately put constraints on that spectrum.

For analog signals such as used in closed access television (CATV) or "radio over fiber" links spectral characteristics are given in terms of various bandwidth measures. However digital signals consist of our main focus here and in the ITU-T G series optical specifications. In this case the spectral characteristics can be more accurately inferred from the modulation format and the bit rate.

Although Non-Return to Zero (NRZ) is currently the dominant form of optical modulation, new modulation formats are being researched [Winzer06] and deployed. With a choice in modulation formats we no longer have a one to one relationship between digital bandwidth in bytes or bits per second and the amount of optical spectrum (optical bandwidth) consumed. To simplify the specification of optical signals

the ITU-T, in recommendation G.959.1, combined a rate bound and modulation format designator [G.959.1]. For example, two of the signal classes defined in [G.959.1] are:

Optical tributary signal class NRZ 1.25G:

> "Applies to continuous digital signals with non-return to zero line coding, from nominally 622 Mbit/s to nominally 1.25 Gbit/s. Optical tributary signal class NRZ 1.25G includes a signal with STM-4 bit rate according to ITU-T Rec. G.707/Y.1322." Note that Gigabit Ethernet falls into this signaling class as well.

Optical tributary signal class RZ 40G:

> "Applies to continuous digital signals with return to zero line coding, from nominally 9.9 Gbit/s to nominally 43.02 Gbit/s. Optical tributary signal class RZ 40G includes a signal with STM-256 bit rate according to ITU-T Rec. G.707/Y.1322 and OTU3 bit rate according to ITU-T Rec. G.709/Y.1331."

From a modeling perspective we have:

- Analog signals: bandwidth parameters, e.g., 3dB parameters and similar.

- Digital signals: there are predefined modulation bit rate classes that we can encode.

This information can be important in constraining route selection, for example some signals may not be compatible with some links or wavelength converters. In addition it lets the endpoints understand if it can process the signal.

### 3.2.3. Signal Rates and Error Correction

Although, the spectral characteristics of a signal determine its basic compatibility with a WDM system, more information is generally needed for various processing activities such as regeneration and reception. Many digital signals such as Ethernet, G.709, and SDH have well defined encoding which includes forward error correction (FEC). However many subsystem vendors offer additional FEC options for a given signal type. The use of different FECs can lead to different overall signal rates. If the FEC and rate used is not compatible between the sender and receiver the signal can not be correctly processed. Note that the rates of "standard" signals may be extended to accommodate different payloads.  For example there are transmitters capable of directly mapping 10GE LAN-PHY traffic into G.709 ODU2 frame with slightly higher clock rate [G.Sup43].

### 3.3. ROADMs, OXCs, Splitters, Combiners and FOADMs

Definitions of various optical devices and their parameters can be found in [G.671], we only look at a subset of these and their non-impairement related properties.

#### 3.3.1. Reconfigurable Add/Drop Multiplexers and OXCs

Reconfigurable add/drop optical multiplexers (ROADM) have matured and are available in different forms and technologies [Basch06]. This is a key technology that allows wavelength based optical switching. A classic degree-2 ROADM is shown in Figure 1.

```
        Line side ingress    +---------------------+  Line side egress
                         --->|                     |--->
                             |                     |
                             |        ROADM        |
                             |                     |
                             |                     |
                             +---------------------+
                                 | | | |  o o o o
                                 | | | |  | | | |
                                 O O O O  | | | |
         Tributary Side:   Drop (egress)  Add (ingress)
```

Figure 1 Degree-2 ROADM

The key feature across all ROADM types is their highly asymmetric switching capability. In the ROADM of Figure 1, the "add" ingress ports can only egress on the line side egress port and not on any of the "drop" egress ports. The degree of a ROADM or switch is given by the number of line side ports (ingress and egress) and does not include the number of "add" or "drop" ports. Sometimes the "add" "drop" ports are also called tributary ports. As the degree of the ROADM increases beyond two it can have properties of both a switch (OXC) and a multiplexer and hence we must know the switched connectivity offered by such a network element to effectively utilize it. A straight forward way to do this is via a "switched connectivity" matrix A where Amn = 0 or 1, depending upon whether a wavelength on ingress port m can be connected to egress port n [Imajuku]. For the ROADM of Figure 1 the switched connectivity matrix can be expressed as

$$A = \begin{array}{lccccc}
\text{Ingress} & \text{Egress Port} & & & & \\
\text{Port} & \#1 & \#2 & \#3 & \#4 & \#5 \\
\hline
\#1: & 1 & 1 & 1 & 1 & 1 \\
\#2 & 1 & 0 & 0 & 0 & 0 \\
\#3 & 1 & 0 & 0 & 0 & 0 \\
\#4 & 1 & 0 & 0 & 0 & 0 \\
\#5 & 1 & 0 & 0 & 0 & 0
\end{array}$$

Where ingress ports 2-5 are add ports, egress ports 2-5 are drop ports and ingress port #1 and egress port #1 are the line side (WDM) ports.

For ROADMs this matrix will be very sparse, and for OXCs the complement of the matrix will be very sparse, compact encodings and usage including high degree ROADMs/OXCs are given in [WSON-Encode].

Additional constraints may also apply to the various ports in a ROADM/OXC. In the literature of optical switches and ROADMs the following restrictions/terms are used:

Colored port: An ingress or more typically an egress (drop) port restricted to a single channel of fixed wavelength.

Colorless port: An ingress or more typically an egress (drop) port restricted to a single channel of arbitrary wavelength.

In general a port on a ROADM could have any of the following wavelength restrictions:

- Multiple wavelengths, full range port
- Single wavelength, full range port
- Single wavelength, fixed lambda port
- Multiple wavelengths, reduced range port (like wave band switching)

To model these restrictions we need two pieces of information for each port: (a) number of wavelengths, (b) wavelength range and spacing.  Note that this information is relatively static. More complicated wavelength constraints are modeled in [WSON-Info].

### 3.3.2. Splitters

An optical splitter consists of a single ingress port and two or more egress ports. The ingress optical signaled is essentially copied (with loss) to all egress ports.

Using the modeling notions of section 3.3.1. the ingress and egress ports of a splitter would have the same wavelength restrictions. In addition we can describe a splitter by a connectivity matrix Amn as follows:

$$A = \begin{array}{l|ccccc} \text{Ingress} & \multicolumn{5}{l}{\text{Egress Port}} \\ \text{Port} & \#1 & \#2 & \#3 & \ldots & \#N \\ \hline \#1 & 1 & 1 & 1 & \ldots & 1 \end{array}$$

The difference from a simple ROADM is that this is not a switched connectivity matrix but the fixed connectivity matrix of the device.

### 3.3.3. Combiners

A optical combiner is somewhat the dual of a splitter in that it has a single multi-wavelength egress port and multiple ingress ports. The contents of all the ingress ports are copied and combined to the single egress port.  The various ports may have different wavelength restrictions. It is generally the responsibility of those using the combiner to assure that wavelength collision does not occur on the egress port. The fixed connectivity matrix Amn for a combiner would look like:

$$A = \begin{array}{l|c} \text{Ingress} & \text{Egress Port} \\ \text{Port} & \#1 \\ \hline \#1: & 1 \\ \#2 & 1 \\ \#3 & 1 \\ \ldots & 1 \\ \#N & 1 \end{array}$$

### 3.3.4. Fixed Optical Add/Drop Multiplexers

A fixed optical add/drop multiplexer can alter the course of an ingress wavelength in a preset way. In particular a particular wavelength (or waveband) from a line side ingress port would be dropped to a particular "tributary" egress port. Depending on the device's fixed configuration that same wavelength may or may not be

"continued" to the line side egress port ("drop and continue" operation). Further there may exist tributary ingress ports ("add" ports) whose signals are combined with each other and "continued" line side signals.

In general to represent the routing properties of an FOADM we need a fixed connectivity matrix Amn as previously discussed and we need the precise wavelength restrictions for all ingress and egress ports. From the wavelength restrictions on the tributary egress ports (drop ports) we can see what wavelengths have been dropped. From the wavelength restrictions on the tributary ingress (add) ports we can see which wavelengths have been added to the line side egress port. Finally from the added wavelength information and the line side egress wavelength restrictions we can infer which wavelengths have been continued.

To summarize, the modeling methodology introduced in section 3.3.1. consisting of a connectivity matrix and port wavelength restrictions can be used to describe a large set of fixed optical devices such as combiners, splitters and FOADMs. Hybrid devices consisting of both switched and fixed parts are modeled in [WSON-Info].

### 3.4. Wavelength Converters

Wavelength converters take an ingress optical signal at one wavelength and emit an equivalent content optical signal at another wavelength on egress. There are currently two approaches to building wavelength converters. One approach is based on optical to electrical to optical (OEO) conversion with tunable lasers on egress. This approach can be dependent upon the signal rate and format, i.e., this is basically an electrical regenerator combined with a tunable laser. The other approach performs the wavelength conversion, optically via non-linear optical effects, similar in spirit to the familiar frequency mixing used in radio frequency systems, but significantly harder to implement. Such processes/effects may place limits on the range of achievable conversion. These may depend on the wavelength of the input signal and the properties of the converter as opposed to only the properties of the converter in the OEO case. Different WSON system designs may choose to utilize this component to varying degrees or not at all.

Current or envisioned contexts for wavelength converters are:

1. Wavelength conversion associated with OEO switches and tunable laser transmitters. In this case there are plenty of converters to go around since we can think of each tunable output laser transmitter on an OEO switch as a potential wavelength converter.

2. Wavelength conversion associated with ROADMs/OXCs. In this case we may have a limited amount of conversion available. Conversion could be either all optical or via an OEO method.

3. Wavelength conversion associated with fixed devices such as FOADMs. In this case we may have a limited amount of conversion. Also in this case the conversion may be used as part of light path routing.

Based on the above contexts a tentative modeling approach for wavelength converters could be as follows:

1. Wavelength converters can always be modeled as associated with network elements. This includes fixed wavelength routing elements.

2. A network element may have full wavelength conversion capability, i.e., any ingress port and wavelength, or a limited number of wavelengths and ports. On a box with a limited number of converters there also may exist restrictions on which ports can reach the converters. Hence regardless of where the converters actually are we can associate them with ingress ports.

3. Wavelength converters have range restrictions that are either independent or dependent upon the ingress wavelength. [TBD: for those that depend on ingress wavelength can we have a standard formula? Also note that this type of converter introduces additional optical impairments.]

4. Wavelength converters that are O-E-O based will have a restriction based on the modulation format and transmission speed.

Note that since O-E-O wavelength converters also serve as regenerators we can include regenerators in our model of wavelength converters. O-E-O Regenerators come in three general types known as 1R, 2R, and 3R regenerators. 1R regenerators re-amplify the signal to combat attenuation, 2R regenerators reshape as well as amplify the signal, 3R regenerators amplify, reshape and retime the signal. As we go from 1R to 3R regenerators the signal is ''cleaned up'' better but at the same time the regeneration process becomes more dependent on the signal characteristics such as format and rate.

In WSONs where wavelength converters are sparse we may actually see a light path appear to loop or ''backtrack'' upon itself in order to reach a wavelength converter prior to continuing on to its destination. The lambda used on the "detour" out to the wavelength converter would be different from that coming back from the "detour" to the wavelength converter.

A model for an O-E-O wavelength converter would consist of:

- Input lambda or frequency range
- Output lambda or frequency range
- Equivalent regeneration level (1R, 2R, 3R)
- Signal restrictions if a 2R or 3R regeneration: formats and rates

[FFS: Model for an all optical wavelength converter]

# 4. Routing and Wavelength Assignment and the Control Plane

In wavelength switched optical networks consisting of tunable lasers and wavelength selective switches with wavelength converters on every interface, path selection is similar to the MPLS and TDM circuit switched cases in that the labels, in this case wavelengths (lambdas), have only local significance. That is, a wavelength-convertible network with full wavelength-conversion capability at each node is equivalent to a circuit-switched TDM network with full time slot interchange capability; thus, the routing problem needs to be addressed only at the level of the traffic engineered (TE) link choice, and wavelength assignment can be resolved locally by the switches on a hop-by-hop basis.

However, in the limiting case of an optical network with no wavelength converters, a light path (optical channel - OCh -) needs a route from source to destination and must pick a single wavelength that can be used along that path without "colliding" with the wavelength used by any other light path that may share an optical fiber. This is sometimes referred to as a "wavelength continuity constraint". To ease up on this constraint while keeping network costs in check a limited number of wavelength converters maybe introduce at key points in the network [Chu03].

In the general case of limited or no wavelength converters this computation is known as the Routing and Wavelength Assignment (RWA) problem [HZang00]. The "hardness" of this problem is well documented. There, however, exist a number of reasonable approximate methods for its solution [HZang00].

The inputs to the basic RWA problem are the requested light paths source and destination, the networks topology, the locations and capabilities of any wavelength converters, and the wavelengths available on each optical link. The output from an algorithm solving the RWA problem is an explicit route through ROADMs, a wavelength for the optical transmitter, and a set of locations (generally associated

with ROADMs or switches) where wavelength conversion is to occur and the new wavelength to be used on each component link after that point in the route.

It is to be noted that choice of specific RWA algorithm is out of the scope for this document. However there are a number of different approaches to dealing with the RWA algorithm that can affect the division of effort between signaling, routing and PCE.

## 4.1. Architectural Approaches to RWA

Two general computational approaches are taken to solving the RWA problem some algorithms utilize a two step procedure of path selection followed by wavelength assignment, and others solve the problem in a combined fashion.

In the following, three different ways of performing RWA in conjunction with the control plane are considered. The choice of one of these architectural approaches over another generally impacts the demands placed on the various control plane protocols.

### 4.1.1. Combined RWA (R&WA)

In this case, a unique entity is in charge of performing routing and wavelength assignment. This choice assumes that computational entity has sufficient WSON network link/nodal information and topology to be able to compute RWA. This solution relies on a sufficient knowledge of network topology, of available network resources and of network nodes capabilities. This knowledge has to be accessible to the entity performing the routing and wavelength assignment.

This solution is compatible with most known RWA algorithms, and in particular those concerned with network optimization. On the other hand, this solution requires up-to-date and detailed network information dissemination.

Such a computational entity could reside in two different logical places:

- In a separate Path Computation Element (PCE) which hence owns the complete and updated knowledge of network state and provides path computation services to node.

- In the Ingress node, in that case all nodes have the R&WA functionality; the knowledge of the network state is obtained by a periodic flooding of information provided by the other nodes.

### 4.1.2. Separated R and WA (R+WA)

In this case a first entity performs routing, while a second performs wavelength assignment. The first entity furnishes one or more paths to the second entity that will perform wavelength assignment and possibly final path selection.

As the entities computing the path and the wavelength assignment are separated, this constrains the class of RWA algorithms that may be implemented. Although it may seem that algorithms optimizing a joint usage of the physical and spectral paths are excluded from this solution, many practical optimization algorithms only consider a limited set of possible paths, e.g., as computed via a k-shortest path algorithm [Ozdaglar03]. Hence although there is no guarantee that the selected final route and wavelength offers the optimal solution by allowing multiple routes to pass to the wavelength selection process reasonable optimization can be performed.

The entity performing the routing assignment needs the topology information of the network, whereas the entity performing the wavelength assignment needs information on the network available resources and on network nodes capabilities.

### 4.1.3. Routing and Distributed WA (R+DWA)

In this case a first entity performs routing, while wavelength assignment is performed on a hop-by-hop manner along the previously computed route. This mechanism relies on updating of a list of potential wavelengths used to ensure the wavelength continuity constraint.

As currently specified, the GMPLS protocol suite signaling protocol can accommodate such an approach. Per [RFC3471], the Label Set selection works according to an AND scheme. Each hop restricts the Label Set sent to the next hop from the one received from the previous hop by performing an AND operation between the wavelength referred by the labels it includes with the one available on the ongoing interface. The constraint to perform this AND operation is up to the node local policy (even if one expects a consistent policy configuration throughout a given transparency domain). When wavelength conversion is performed at an intermediate node, a new Label Set is generated. The egress nodes selects one label in the Label Set received at the node, which is also up to the node local policy.

Depending on these policies a spectral assignment may not be found or one consuming too many conversion resources relatively to what a dedicated wavelength assignment policy would have achieved. Hence, this may generate higher blocking probabilities in a heavily loaded network.

On the one hand, this solution may be empowered with some signaling extensions to ease its functioning and possibly enhance its performances relatively to blocking. On the other hand this solution is not stressing the information dissemination processes.

The first entity may be a PCE or the ingress node of the LSP. This solution is applicable inside network where resource optimization is not the most crucial constraint.

## 4.2. Conveying information needed by RWA

The previous sections have characterized WSONs and lightpath requests. In particular high level models of the information by the RWA process were presented. We can view this information as either static, changing with hardware changes (including possibly failures), or dynamic, can change with subsequent lightpath provisioning. The timeliness in which an entity involved in the RWA process is notified of such changes is fairly situational. For example, for network restoration purposes, learning of a hardware failure or of new hardware coming online to provide restoration capability can be critical.
Currently there are various methods for communicating RWA relevant information, these include, but are not limited to:

- Existing control plane protocols such as GMPLS routing and signaling. Note that routing protocols can be used to convey both static and dynamic information. Static information currently conveyed includes items like router options and such.

- Management protocols such as NetConf, SNMPv3, CLI, CORBA, or others.

- Directory services and accompanying protocols. These are good for the dissemination of relatively static information. Not intended for dynamic information.

- Other techniques for dynamic information: messaging straight from NEs to PCE to avoid flooding. This would be useful if the number of PCEs is significantly less than number of WSON NEs. Or other ways to limit flooding to "interested" NEs.

Mechanisms to improve scaling of dynamic information:

- Tailor message content to WSON. For example the use of wavelength ranges, or wavelength occupation bit maps.

Utilize incremental updates if feasible.

### 4.3. Lightpath Temporal Characteristics

The temporal characteristics of a light path connection is another aspect that can affect the choice of solution to the RWA process. For our purposes here we look at the timeliness of connection establishment/teardown, and the duration of the connection.

Connection Establishment/Teardown Timeliness can be thought of in approximately three time frames:

1. Time Critical: For example those lightpath establishments used for restoration of service or other high priority real time service requests.

2. Soft time bounds: This is a more typical new connection request. While expected to be responsive, there should be more time to take into account network optimization.

3. Scheduled or Advanced reservations. Here lightpath connections are requested significantly ahead of their intended "in service" time. There is the potential for significant network optimization if multiple lightpaths can be computed concurrently to achieve network optimization objectives.

Lightpath connection duration has typically been thought of as approximately three time frames:

1. Dynamic: those lightpaths with relatively short duration (holding times).

2. Pseudo-static: lightpaths with moderately long durations.

3. Static: lightpaths with long durations.

Different types of RWA algorithms have been developed for dealing with dynamic versus pseudo-static conditions. These can address service provider's needs for: (a) network optimization, (b) restoration, and (c) highly dynamic lightpath provisioning.

Hence we can model timescale related lightpath requirements via the following notions:

- Batch or Sequential light path connection requests

- o Timeliness of Connection establishment
- o Duration of lightpath connection

## 5. GMPLS & PCE Implications

The presence and amount of wavelength conversion available at a wavelength switching interface has an impact on the information that needs to be transferred by the control plane (GMPLS) and the PCE architecture. Current GMPLS and PCE standards can address the full wavelength conversion case so the following will only address the limited and no wavelength conversion cases.

### 5.1. Implications for GMPLS signaling

Basic support for WSON signaling already exists in GMPLS with the lambda (value 9) LSP encoding type [RFC3471], or for G.709 compatible optical channels, the LSP encoding type (value = 13) "G.709 Optical Channel" from [RFC4328]. However a number of practical issues arise in the identification of wavelengths and signals, and distributed wavelength assignment processes which are discussed below.

#### 5.1.1. Identifying Wavelengths and Signals

As previously stated a global fixed mapping between wavelengths and labels simplifies the characterization of WDM links and WSON devices. Furthermore such a mapping as described in [Otani] eases communication between PCE and WSON PCCs.

An alternative to a global network map of labels to wavelengths would be to use LMP to assign the map for each link then convey that information to any path computation entities, e.g., label switch routers or stand alone PCEs. The local label map approach will require the label-set contents in the RSVP-TE Path message to be translated every time the map changes between an incoming link and the outgoing link.

In the future, it maybe worthwhile to define traffic parameters for lambda LSPs that include a signal type field that includes modulation format/rate information. This is similar to what was done in reference [RFC4606] for SONET/SDH signal types.

#### 5.1.2. Combined RWA/Separate Routing WA support

In either the combined RWA or separate routing WA cases, the node initiating the signaling will have a route from the source to destination along with the wavelengths (generalized labels) to be used along portions of the path. Current GMPLS signaling supports an

explicit route object (ERO) and within an ERO an ERO Label subobject can be use to indicate the wavelength to be used at a particular node. In case the local label map approach is used the label sub-object entry in the ERO has to be translated appropriately.

### 5.1.3. Distributed Wavelength Assignment: Unidirectional, No Converters

GMPLS signaling for a uni-directional lightpath LSP allows for the use of a label set object in the RSVP-TE path message. The processing of the label set object to take the intersection of available lambdas along a path can be performed resulting in the set of available lambda being known to the destination that can then use a wavelength selection algorithm to choose a lambda. For example, the following is a non-exhaustive subset of wavelength assignment (WA) approaches discussed in [HZang00]:

1. Random: Looks at all available wavelengths for the light path then chooses from those available at random.

2. First Fit: Wavelengths are ordered, first available (on all links) is chosen.

3. Most Used: Out of the wavelengths available on the path attempts to select most use wavelength in network.

4. Least Loaded: For multi-fiber networks. Chooses the wavelength j that maximizes minimum of the difference between the number of fibers on link l and the number of fibers on link l with wavelength j occupied.

As can be seen from the above short list, wavelength assignment methods have differing information or processing requirements. The information requirements of these methods are as follows:

1. Random: nothing more than the available wavelength set.

2. First Fit: nothing more than the available wavelength set.

3. Most Used: the available wavelength set and information on global wavelength use in the network.

4. Least Loaded: the available wavelength set and information concerning the wavelength dependent loading for each link (this applies to multi-fiber links). This could be obtained via global information or via supplemental information passed via the signaling protocol.

In case (3) above the global information needed by the wavelength assignment could be derived from suitably enhanced GMPLS routing. Note however this information need not be accurate enough for combined RWA computation. Currently, GMPLS signaling does not provide a way to indicate that a particular wavelength assignment algorithm should be used.

#### 5.1.4. Distributed Wavelength Assignment: Unidirectional, Limited Converters

The previous outlined the case with no wavelength converters. In the case of wavelength converters, nodes with wavelength converters would need to make the decision as to whether to perform conversion. One indicator for this would be that the set of available wavelengths which is obtained via the intersection of the incoming label set and the egress links available wavelengths is either null or deemed too small to permit successful completion.

At this point the node would need to remember that it will apply wavelength conversion and will be responsible for assigning the wavelength on the previous lambda-contiguous segment when the RSVP-TE RESV message passes by. The node will pass on an enlarged label set reflecting only the limitations of the wavelength converter and the egress link. The record route option in RVSP-TE signaling can be used to show where wavelength conversion has taken place.

#### 5.1.5. Distributed Wavelength Assignment: Bidirectional, No Converters

There are potential issues in the case of a bi-directional lightpath which requires the use of the same lambda in both directions. We can try to use the above procedure to determine the available bidirectional lambda set if we use the interpretation that the available label set is available in both directions. However, a problem, arises in that bidirectional LSPs setup, according to [RFC3471] section 4.1, is indicated by the presence of an upstream label in the path message.

However, until the intersection of the available label sets is obtained, e.g., at the destination node and the wavelength assignment algorithm has been run the upstream label information will not be available. Hence currently distributed wavelength assignment with bidirectional lightpaths is not supported.

## 5.2. Implications for GMPLS Routing

GMPLS routing [RFC4202] currently defines an interface capability descriptor for "lambda switch capable" (LSC) which we can use to describe the interfaces on a ROADM or other type of wavelength selective switch. In addition to the topology information typically conveyed via an IGP, we would need to convey the following subsystem properties to minimally characterize a WSON:

1. WDM Link properties (allowed wavelengths).

2. Laser Transmitters (wavelength range).

3. ROADM/FOADM properties (connectivity matrix, port wavelength restrictions).

4. Wavelength Converter properties (per network element, may change if a common limited shared pool is used).

In most cases we should be able to combine items (1) and (2) into the information in item (3). Except for the number of wavelength converters that are available in a shared pool, and the previous information is fairly static. In the next two sections we discuss dynamic available link bandwidth information.

### 5.2.1. Need for Wavelength-Specific Maximum Bandwidth Information

Difficulties are encountered when trying to use the bandwidth accounting methods of [RFC4202] and [RFC3630] to describe the availability of wavelengths on a WDM link. The current RFCs give three link resource measures: Maximum Bandwidth, Maximum Reservable Bandwidth, and Unreserved Bandwidth. Although these can be used to describe a WDM span they do not provide the fundamental information needed for RWA. We are not given the maximum bandwidth per wavelength for the span. If we did then we could use the aforementioned measures to tell us the maximum wavelength count and the number of available wavelengths.

For example, suppose we have a 32 channel WDM span, and that the system in general supports ITU-T NRZ signals up to NRZ 10Gbps. Further suppose that the first 20 channels are carrying 1Gbps Ethernet, then the maximum bandwidth would be 320Gbps and the maximum reservable bandwidth would be 120Gbps (12 wavelengths). Alternatively, consider the case where the first 8 channels are carrying 2.5Gbps SDH STM-16 channels, then the maximum bandwidth would still be 320Gbps and the maximum reservable bandwidth would be 240Gbps (24 wavelengths).

Such information would be useful in the routing with distributed WA approach of section 4.1.3.

### 5.2.2. Need for Wavelength-Specific Availability Information

Even if we know the number of available wavelengths on a link, we actually need to know which specific wavelengths are available and which are occupied if we are going to run a combined RWA process or separate WA process as discussed in sections 4.1.1. 4.1.2.  This is currently not possible with GMPLS routing extensions.

In the routing extensions for GMPLS [RFC4202], requirements for layer-specific TE attributes are discussed. The RWA problem for optical networks without wavelength converters imposes an additional requirement for the lambda (or optical channel) layer: that of knowing which specific wavelengths are in use. Note that current dense WDM (DWDM) systems range from 16 channels to 128 channels with advanced laboratory systems with as many as 300 channels. Given these channel limitations and if we take the approach of a global wavelength to label mapping or furnishing the local mappings to the PCEs then representing the use of wavelengths via a simple bit-map is feasible.

### 5.2.3. Relationship to Link Bundling and Layering

When dealing with static DWDM systems, particularly from a SONET/SDH or G.709 digital wrapper layer, each lambda looks like a separate link. Typically a bunch of unnumbered links, as supported in GMPLS routing extensions [RFC4202], would be used to describe a static DWDM system. In addition these links can be bundled into a TE link ([RFC4202], [RFC4201]) for more efficient dissemination of resource information. However, in the case discussed here we want to control a dynamic WDM layer and must deal with wavelengths as labels and not just as links or component links from the perspective of an upper (client) layer. In addition, a typical point to point optical cable contains many optical fibers and hence it may be desirable to bundle these separate fibers into a TE link. Note that in the no wavelength conversion or limited wavelength conversion situations that we will need information on wavelength usage on the individual component links.

### 5.2.4. WSON Routing Information Summary

The following table summarizes the WSON information that could be conveyed via GMPLS routing and attempts to classify that information as to its static or dynamic nature and whether that information would tend to be associated with either a link or a node.

| Information | Static/Dynamic | Node/Link |
|---|---|---|
| Connectivity matrix | Static | Node |
| Per port wavelength restrictions | Static | Node(1) |
| WDM link (fiber) lambda ranges | Static | Link |
| WDM link channel spacing | Static | Link |
| Laser Transmitter range | Static | Link(2) |
| Wavelength conversion capabilities | Static(3) | Node |
| Maximum bandwidth per Wavelength | Static | Link |
| Wavelength Availability | Dynamic(4) | Link |

Notes:

1. These are the per port wavelength restrictions of an optical device such as a ROADM and are independent of any optical constraints imposed by a fiber link.

2. This could also be viewed as a node capability.

3. This could be dynamic in the case of a limited pool of converters where the number available can change with connection establishment. Note we may want to include regeneration capabilities here since OEO converters are also regenerators.

4. Not necessarily needed in the case of distributed wavelength assignment via signaling.

While the full complement of the information from the previous table is needed in the Combined RWA and the separate Routing and WA architectures, in the case of Routing + distribute WA via signaling we only need the following information:

| Information | Static/Dynamic | Node/Link |
|---|---|---|
| Connectivity matrix | Static | Node |
| Wavelength conversion capabilities | Static(3) | Node |

Information models and compact encodings for this information is provided in [WSON-Info].

### 5.3. Optical Path Computation and Implications for PCE

As previously noted the RWA problem can be computationally intensive [HZang00]. Such computationally intensive path computations and optimizations were part of the impetus for the PCE (path computation element) architecture.

As the PCEP defines the procedures necessary to support both sequential [PCEP] and global concurrent path computations [PCE-GCO], PCE is well positioned to support WSON-enabled RWA computation with some protocol enhancement.

Implications for PCE generally fall into two main categories: (a) lightpath constraints and characteristics, (b) computation architectures.

#### 5.3.1. Lightpath Constraints and Characteristics

For the varying degrees of optimization that may be encountered in a network the following models of bulk and sequential lightpath requests are encountered:

- Batch optimization, multiple lightpaths requested at one time.

- Lightpath(s) and backup lightpath(s) requested at one time.

- Single lightpath requested at a time.

PCEP and PCE-GCO can be readily enhanced to support all of the potential models of RWA computation.

Lightpath constraints include:

- Bidirectional Assignment of wavelengths

- Possible simultaneous assignment of wavelength to primary and backup paths.

- Tuning range constraint on optical transmitter.

Lightpath characteristics can include:

- Duration information (how long this connection may last)

- Timeliness/Urgency information (how quickly is this connection needed)

### 5.3.2. Computation Architecture Implications

When a PCE performs a combined RWA computation per section 4.1.1. it requires accurate an up to date wavelength utilization on all links in the network.

When a PCE is used to perform wavelength assignment (WA) in the separate routing WA architecture then the entity requesting WA needs to furnish the pre-selected route to the PCE as well as any of the lightpath constraints/characteristics previously mentioned. This architecture also requires the PCE performing WA to have accurate and up to date network wavelength utilization information.

When a PCE is used to perform routing in a routing with distribute WA architecture, then the PCE does not necessarily need the most up to date network wavelength utilization information, however timely information can contributed to reducing failed signaling attempts related to blocking.

### 5.3.3. Discovery of RWA Capable PCEs

The algorithms and network information needed for solving the RWA are somewhat specialized and computationally intensive hence not all PCEs within a domain would necessarily need or want this capability. Hence, it would be useful via the mechanisms being established for PCE discovery [RFC5088] to indicate that a PCE has the ability to deal with the RWA problem. Reference [RFC5088] indicates that a sub-TLV could be allocated for this purpose.

Recent progress on objective functions in PCE [PCE-OF] would allow the operators to flexibly request differing objective functions per their need and applications. For instance, this would allow the operator to choose an objective function that minimizes the total network cost associated with setting up a set of paths concurrently. This would also allow operators to choose an objective function that results in a most evenly distributed link utilization.

This implies that PCEP would easily accommodate wavelength selection algorithm in its objective function to be able to optimize the path computation from the perspective of wavelength assignment if chosen by the operators.

## 5.4. Scaling Implications

This section provides a summary of the scaling issue for WSON routing, signaling and path computation introduced by the concepts discussed in this document.

### 5.4.1. Routing

In large WSONs label availability and cross connect capability information being advertised may generate a significant amount of routing information.

### 5.4.2. Signaling

When dealing with a large number of simultaneous end-to-end wavelength service requests and service deletions the network may have to process a significant number of forward and backward service messages. Also, similar situation possibly happens in the case of link or node failure, if the WSON support dynamic restoration capability.

### 5.4.3. Path computation

If a PCE is handling path computation requests for end-to-end wavelength services within the WSON, then the complexity of the network and number of service path computation requests being sent to the PCE may have an impact on the PCEs ability to process requests in a timely manner.

## 5.5. Summary of Impacts by RWA Architecture

The following table summarizes for each RWA strategy the list of mandatory ("M") and optional ("O") control plane features according to GMPLS architectural blocks:

- o Information required by the path computation entity,
- o LSP request parameters used in either PCC to PCE situations or in signaling,
- o RSVP-TE LSP signaling parameters used in LSP establishment.

The table shows which enhancements are common to all architectures (R&WA, R+WA, R+DWA), which apply only to R&WA and R+WA (R+&WA), and which apply only to R+DWA.

| Feature | ref | Common | | R+&WA | | R+DWA | |
|---|---|---|---|---|---|---|---|
| | | M | O | M | O | M | O |
| Generalized Label for Wavelength | 5.1.1 | x | | | | | |
| Flooding of information for the | | | | | | | |

| | | | | | | | |
|---|---|---|---|---|---|---|---|
| routing phase | | | | | | | |
| Node features | 3.3 | | | | | | |
| Node type | | | x | | | | |
| spectral X-connect constraint | | | | x | | | |
| port X-connect constraint | | | | x | | | |
| Transponders availability | | | x | | | | |
| Transponders features | 3.2 | | x | | | | |
| Converter availability | | | | x | | | |
| Converter features | 3.4 | | | x | | | x |
| TE-parameters of WDM links | 3.1 | x | | | | | |
| Total Number of wavelength | | x | | | | | |
| Number of wavelengths available | | x | | | | | |
| Grid spacing | | x | | | | | |
| Wavelength availability on links | 5.2 | | | x | | | |
| LSP request parameters | | | | | | | |
| Signal features | 5.1 | | x | | | x | |
| Modulation format | | | x | | | x | |
| Modulation parameters | | | x | | | x | |
| Specification of RWA method | 5.1 | | x | | | x | |
| LSP time features | 4.3 | | x | | | | |
| Enriching signaling messages | | | | | | | |
| Signal features | 5.1 | | | | | x | |

## 6. Security Considerations

This document has no requirement for a change to the security models within GMPLS and associated protocols. That is the OSPF-TE, RSVP-TE, and PCEP security models could be operated unchanged.

However satisfying the requirements for RWA using the existing protocols may significantly affect the loading of those protocols. This makes the operation of the network more vulnerable to denial of service attacks. Therefore additional care maybe required to ensure that the protocols are secure in the WSON environment.

Furthermore the additional information distributed in order to address the RWA problem represents a disclosure of network capabilities that an operator may wish to keep private. Consideration should be given to securing this information.

## 7. IANA Considerations

This document makes no request for IANA actions.

## 8. Acknowledgments

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This document was prepared using 2-Word-v2.0.template.dot.

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