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Framework for GMPLS and Path Computation Element (PCE) Control
of Wavelength Switched Optical Networks (WSONs)

Abstract

This document 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 (WSONs). In particular, it examines Routing and Wavelength
Assignment (RWA) of optical paths.

This document focuses on topological elements and path selection
constraints that are common across different WSON environments; as
such, it does not address optical impairments in any depth.

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1. Introduction

   Wavelength Switched Optical Networks (WSONs) are constructed from
   subsystems that include Wavelength Division Multiplexing (WDM) links,
   tunable transmitters and receivers, Reconfigurable Optical Add/Drop
   Multiplexers (ROADMs), wavelength converters, and electro-optical
   network elements. A WSON is a WDM-based optical network in which
   switching is performed selectively based on the center wavelength of
   an optical signal.

   WSONs can differ from other types of GMPLS networks in that many
   types of WSON nodes are highly asymmetric with respect to their
   switching capabilities, compatibility of signal types and network
   elements may need to be considered, and label assignment can be non-
   local. In order to provision an optical connection (an optical path)
   through a WSON certain wavelength continuity and resource
   availability constraints must be met to determine viable and optimal
   paths through the WSON. The determination of paths is known as
   Routing and Wavelength Assignment (RWA).

   Generalized Multi-Protocol Label Switching (GMPLS) [RFC3945] includes
   an architecture and a set of control plane protocols that can be used
   to operate data networks ranging from packet-switch-capable networks,
   through those networks that use Time Division Multiplexing, to WDM
   networks. The Path Computation Element (PCE) architecture [RFC4655]
   defines functional components that can be used to compute and suggest
   appropriate paths in connection-oriented traffic-engineered networks.

   This document provides a framework for applying the GMPLS
   architecture and protocols [RFC3945] and the PCE architecture
   [RFC4655] to the control and operation of WSONs. To aid in this
   process, this document also provides an overview of the subsystems
   and processes that comprise WSONs and describes RWA so that the
   information requirements, both static and dynamic, can be identified
   to explain how the information can be modeled for use by GMPLS and
   PCE systems. This work will facilitate the development of protocol
   solution models and protocol extensions within the GMPLS and PCE
   protocol families.

   Different WSONs such as access, metro, and long haul may apply
   different techniques for dealing with optical impairments; hence,
   this document does not address optical impairments in any depth.
   Note that this document focuses on the generic properties of links,
   switches, and path selection constraints that occur in many types of
   WSONs. See [WSON-Imp] for more information on optical impairments
   and GMPLS.

2. Terminology

   Add/Drop Multiplexer (ADM): An optical device used in WDM networks
   and composed of one or more line side ports and typically many
   tributary ports.

   CWDM: Coarse Wavelength Division Multiplexing.

   DWDM: Dense Wavelength Division Multiplexing.

   Degree: The degree of an optical device (e.g., ROADM) is given by a
   count of its line side ports.

   Drop and continue: A simple multicast feature of some ADMs where a
   selected wavelength can be switched out of both a tributary (drop)
   port and a line side port.

   FOADM: Fixed Optical Add/Drop Multiplexer.

   GMPLS: Generalized Multi-Protocol Label Switching.

   Line side: In a WDM system, line side ports and links can typically
   carry the full multiplex of wavelength signals, as compared to
   tributary (add or drop) ports that typically carry a few (usually
   one) wavelength signals.

   OXC: Optical Cross-Connect. An optical switching element in which a
   signal on any input port can reach any output port.

   PCC: Path Computation Client. Any client application requesting a
   path computation to be performed by the Path Computation Element.

   PCE: Path Computation Element. An entity (component, application, or
   network node) that is capable of computing a network path or route
   based on a network graph and application of computational
   constraints.

   PCEP: PCE Communication Protocol. The communication protocol between
   a Path Computation Client and Path Computation Element.

   ROADM: Reconfigurable Optical Add/Drop Multiplexer. A wavelength-
   selective switching element featuring input and output line side
   ports as well as add/drop tributary ports.

   RWA: Routing and Wavelength Assignment.

   Transparent Network: A Wavelength Switched Optical Network that does
   not contain regenerators or wavelength converters.

Translucent Network: A Wavelength Switched Optical Network that is predominantly transparent but may also contain limited numbers of regenerators and/or wavelength converters.

Tributary: A link or port on a WDM system that can carry significantly less than the full multiplex of wavelength signals found on the line side links/ports. Typical tributary ports are the add and drop ports on an ADM, and these support only a single wavelength channel.

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 (WSONs): 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 range in size from continent-spanning long-haul networks, to metropolitan networks, to residential access networks. In all these cases, the main concern is 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 addition, if electro-optical network elements are used in the WSON, additional compatibility constraints may be imposed by the network elements on various optical signal parameters. The subsequent sections review and model some of the major subsystems of a WSON with an emphasis on those aspects that are of relevance to the control plane. In particular, WDM links, optical transmitters, ROADMs, and wavelength converters are examined.

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. Examples include access networks, metro, long haul, and submarine links. International Telecommunication Union - Telecommunication Standardization Sector (ITU-T) standards exist for various types of fibers. Although fiber can be categorized into Single-Mode Fibers (SMFs) and Multi-Mode Fibers (MMFs), the latter are typically used for short-reach campus and premise applications. SMFs are used for longer-reach applications and are therefore the

primary concern of this document. The following SMF 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      |
---------------------------------------------------------------
```

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 1383 nm. Hence, a discontinuous acceptable
wavelength range for a particular link may be needed and is modeled.
Also, some systems will utilize more than one band. This is
particularly true for CWDM systems.

Current technology subdivides 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, "Spectral grids for WDM applications: DWDM
frequency grid" [G.694.1], describes a DWDM grid defined in terms of
frequency grids of 12.5 GHz, 25 GHz, 50 GHz, 100 GHz, and other
multiples of 100 GHz around a 193.1 THz 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,
"Spectral grids for WDM applications: CWDM wavelength grid"
[G.694.2], describes a CWDM grid defined in terms of wavelength
increments of 20 nm running from 1271 nm to 1611 nm for 18 or so
channels. The number of channels is significantly smaller than the
32-bit GMPLS Label space defined for GMPLS (see [RFC3471]). A label
representation for these ITU-T grids is given in [RFC6205] and
provides a common label format to be used in signaling optical paths.

Further, these ITU-T grid-based labels can also be used to describe
WDM links, ROADM ports, and wavelength converters for the purposes of
path selection.

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 significant system
engineering and a fairly limited range of wavelengths. Hence, the
following information is needed as parameters to perform basic,
impairment-unaware modeling of a WDM link:

o Wavelength range(s): Given a mapping between labels and the ITU-T
   grids, each range could be expressed in terms of a tuple,
   (lambda1, lambda2) or (freq1, freq2), where the lambdas or
   frequencies can be represented by 32-bit integers.

o Channel spacing: Currently, there are five channel spacings used
   in DWDM systems and a single channel spacing defined for CWDM
   systems.

For a particular link, this information is relatively static, as
changes to these properties generally require hardware upgrades.
Such information may be used locally during wavelength assignment via
signaling, similar to label restrictions in MPLS, or used by a PCE in
providing combined RWA.

3.2. Optical Transmitters and Receivers

WDM optical systems make use of optical transmitters and receivers
utilizing different wavelengths (frequencies). Some transmitters are
manufactured for a specific wavelength of operation; that is, the
manufactured frequency cannot be changed. First introduced to reduce
inventory costs, tunable optical transmitters and receivers are
deployed in some systems and allow flexibility in the wavelength used
for optical transmission/reception. Such tunable optics aid in path
selection.

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

o Tunable: Do the transmitters and receivers operate at variable or
   fixed wavelength?

o Tuning range: This is the frequency or wavelength range over which
   the optics can be tuned. With the fixed mapping of labels to
   lambdas as proposed in [RFC6205], this can be expressed as a

      tuple, (lambda1, lambda2) or (freq1, freq2), where lambda1 and
      lambda2 or freq1 and freq2 are the labels representing the lower
      and upper bounds in wavelength.

   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 usable for fast protection applications.

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

   Note that ITU-T recommendations specify many aspects of an optical
   transmitter. Many of these parameters, such as spectral
   characteristics and stability, are used in the design of WDM
   subsystems consisting of transmitters, WDM links, and receivers.
   However, they do not furnish additional information that will
   influence the Label Switched Path (LSP) provisioning in a properly
   designed system.

   Also, note that optical components can degrade and fail over time.
   This presents the possibility of the failure of an LSP (optical path)
   without either a node or link failure. Hence, additional mechanisms
   may be necessary to detect and differentiate this failure from the
   others; for example, one does not want to initiate mesh restoration
   if the source transmitter has failed since the optical transmitter
   will still be failed on the alternate optical path.

3.3. Optical Signals in WSONs

   The fundamental unit of switching in WSONs is intuitively that of a
   "wavelength". The transmitters and receivers in these networks will
   deal with one wavelength at a time, while the switching systems
   themselves can deal with multiple wavelengths at a time. Hence,
   multi-channel DWDM networks with single-channel interfaces are the
   prime focus of this document as opposed to multi-channel interfaces.
   Interfaces of this type are defined in ITU-T Recommendations
   [G.698.1] and [G.698.2]. Key non-impairment-related parameters
   defined in [G.698.1] and [G.698.2] are:

   (a) Minimum channel spacing (GHz)

   (b) Minimum and maximum central frequency

(c) Bitrate/Line coding (modulation) of optical tributary signals

For the purposes of modeling the WSON in the control plane, (a) and
(b) are considered properties of the link and restrictions on the
GMPLS Labels while (c) is a property of the "signal".

3.3.1. Optical Tributary Signals

The optical interface specifications [G.698.1], [G.698.2], and
[G.959.1] all use the concept of an optical tributary signal, which
is defined as "a single channel signal that is placed within an
optical channel for transport across the optical network". Note the
use of the qualifier "tributary" to indicate that this is a single-
channel entity and not a multi-channel optical signal.

There are currently a number of different types of optical tributary
signals, which are known as "optical tributary signal classes".
These are currently characterized by a modulation format and bitrate
range [G.959.1]:

(a) Optical tributary signal class Non-Return-to-Zero (NRZ) 1.25G

(b) Optical tributary signal class NRZ 2.5G

(c) Optical tributary signal class NRZ 10G

(d) Optical tributary signal class NRZ 40G

(e) Optical tributary signal class Return-to-Zero (RZ) 40G

Note that, with advances in technology, more optical tributary signal
classes may be added and that this is currently an active area for
development and standardization. In particular, at the 40G rate,
there are a number of non-standardized advanced modulation formats
that have seen significant deployment, including Differential Phase
Shift Keying (DPSK) and Phase Shaped Binary Transmission (PSBT).

According to [G.698.2], it is important to fully specify the bitrate
of the optical tributary signal. Hence, modulation format (optical
tributary signal class) and bitrate are key parameters in
characterizing the optical tributary signal.

3.3.2. WSON Signal Characteristics

The optical tributary signal referenced in ITU-T Recommendations
[G.698.1] and [G.698.2] is referred to as the "signal" in this
document. This corresponds to the "lambda" LSP in GMPLS. For signal

compatibility purposes with electro-optical network elements, the
following signal characteristics are considered:

1. Optical tributary signal class (modulation format)

2. Forward Error Correction (FEC): whether forward error correction
    is used in the digital stream and what type of error correcting
    code is used

3. Center frequency (wavelength)

4. Bitrate

5. General Protocol Identifier (G-PID) for the information format

The first three items on this list can change as a WSON signal
traverses the optical network with elements that include
regenerators, OEO switches, or wavelength converters.

Bitrate and G-PID would not change since they describe the encoded
bitstream. A set of G-PID values is already defined for lambda
switching in [RFC3471] and [RFC4328].

Note that a number of non-standard or proprietary modulation formats
and FEC codes are commonly used in WSONs. For some digital
bitstreams, the presence of FEC can be detected; for example, in
[G.707], this is indicated in the signal itself via the FEC Status
Indication (FSI) byte while in [G.709], this can be inferred from
whether or not the FEC field of the Optical Channel Transport Unit-k
(OTUk) is all zeros.

3.4. ROADMs, OXCs, Splitters, Combiners, and FOADMs

Definitions of various optical devices such as ROADMs, Optical Cross-
Connects (OXCs), splitters, combiners, and Fixed Optical Add/Drop
Multiplexers (FOADMs) and their parameters can be found in [G.671].
Only a subset of these relevant to the control plane and their non-
impairment-related properties are considered in the following
sections.

3.4.1. Reconfigurable Optical Add/Drop Multiplexers and OXCs

ROADMs are available in different forms and technologies. This is a
key technology that allows wavelength-based optical switching. A
classic degree-2 ROADM is shown in Figure 1.

```
Line side input     +--------------------+  Line side output
          --->|                    |--->
              |                    |
              |        ROADM       |
              |                    |
              |                    |
              +--------------------+
                | | | |   o o o o
                | | | |   | | | |
                o o o o   | | | |
    Tributary Side:   Drop (output)  Add (input)
```
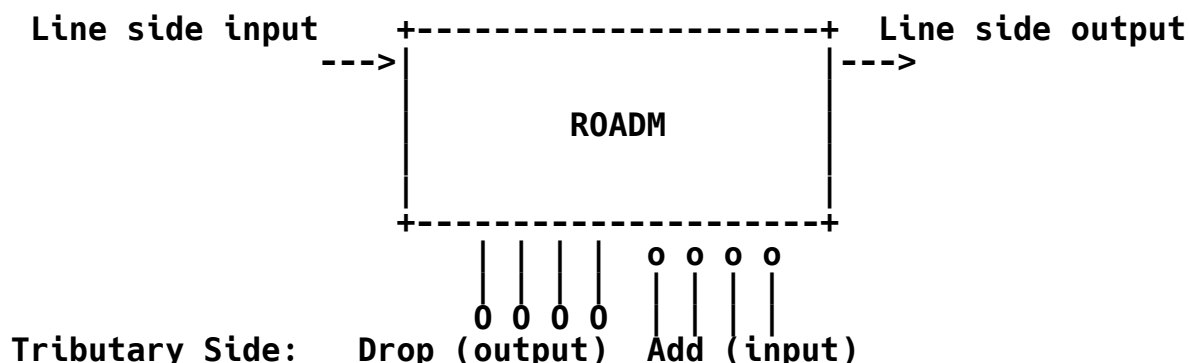
               Figure 1. Degree-2 Unidirectional ROADM

   The key feature across all ROADM types is their highly asymmetric
   switching capability. In the ROADM of Figure 1, signals introduced
   via the add ports can only be sent on the line side output port and
   not on any of the drop ports. The term "degree" is used to refer to
   the number of line side ports (input and output) of a ROADM and does
   not include the number of "add" or "drop" ports. The add and drop
   ports are sometimes 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; hence, it is necessary to know the
   switched connectivity offered by such a network element to
   effectively utilize it. A straightforward way to represent this is
   via a "switched connectivity" matrix A where $A_{mn} = 0$ or 1, depending
   upon whether a wavelength on input port m can be connected to output
   port n [Imajuku]. For the ROADM shown in Figure 1, the switched
   connectivity matrix can be expressed as:

```
            Input    Output Port
            Port     #1 #2 #3 #4 #5
                     --------------
            #1:      1  1  1  1  1
            #2       1  0  0  0  0
      A =   #3       1  0  0  0  0
            #4       1  0  0  0  0
            #5       1  0  0  0  0
```

   where input ports 2-5 are add ports, output ports 2-5 are drop ports,
   and input port #1 and output port #1 are the line side (WDM) ports.

   For ROADMs, this matrix will be very sparse, and for OXCs, the matrix
   will be very dense. Compact encodings and examples, including high-
   degree ROADMs/OXCs, are given in [Gen-Encode]. A degree-4 ROADM is
   shown in Figure 2.

```
                  +-----------------------+
Line side-1    --->|                       |--->    Line side-2
Input (I1)         |                       |        Output (E2)
Line side-1    <---|                       |<---    Line side-2
Output  (E1)       |                       |        Input (I2)
                   |                       |
                   |        ROADM          |
                   |                       |
Line side-3    --->|                       |--->    Line side-4
Input (I3)         |                       |        Output (E4)
Line side-3    <---|                       |<---    Line side-4
Output (E3)        |                       |        Input (I4)
                   |                       |
                  +-----------------------+
                   |  0   |  0   |  0   |  0
                   |  |   |  |   |  |   |  |
                   0  |   0  |   0  |   0  |
Tributary Side:    E5 I5  E6 I6  E7 I7  E8 I8
```
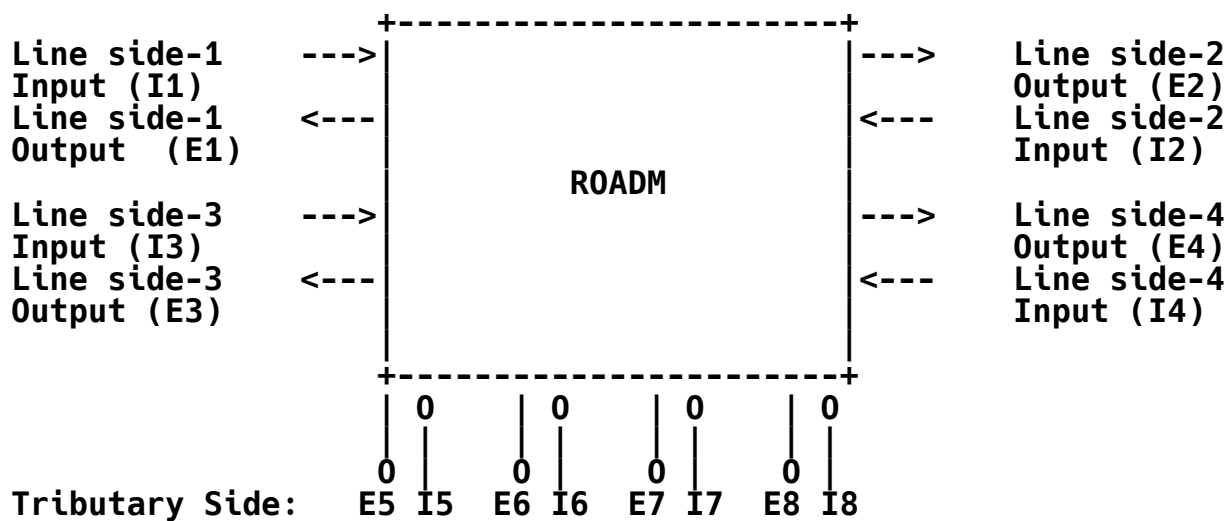
                Figure 2. Degree-4 Bidirectional ROADM

Note that this is a 4-degree example with one (potentially multi-
channel) add/drop per line side port.

Note also that the connectivity constraints for typical ROADM designs
are "bidirectional"; that is, if input port X can be connected to
output port Y, typically input port Y can be connected to output port
X, assuming the numbering is done in such a way that input X and
output X correspond to the same line side direction or the same
add/drop port. This makes the connectivity matrix symmetrical as
shown below.

```
        Input     Output Port
         Port     E1 E2 E3 E4 E5 E6 E7 E8
                  -----------------------
            I1     0  1  1  1  0  1  0  0
            I2     1  0  1  1  0  0  1  0
    A =     I3     1  1  0  1  1  0  0  0
            I4     1  1  1  0  0  0  0  1
            I5     0  0  1  0  0  0  0  0
            I6     1  0  0  0  0  0  0  0
            I7     0  1  0  0  0  0  0  0
            I8     0  0  0  1  0  0  0  0
```

where I5/E5 are add/drop ports to/from line side-3, I6/E6 are
add/drop ports to/from line side-1, I7/E7 are add/drop ports to/from
line side-2, and I8/E8 are add/drop ports to/from line side-4. Note
that diagonal elements are zero since loopback is not supported in
the example. If ports support loopback, diagonal elements would be
set to one.

Additional constraints may also apply to the various ports in a
ROADM/OXC. The following restrictions and terms may be used:

o Colored port: an input or, more typically, an output (drop) port
   restricted to a single channel of fixed wavelength

o Colorless port: an input or, more typically, an output (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:

o Multiple wavelengths, full range port

o Single wavelength, full range port

o Single wavelength, fixed lambda port

o Multiple wavelengths, reduced range port (for example wave band
   switching)

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

3.4.2. Splitters

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

Using the modeling notions of Section 3.4.1, the input and output
ports of a splitter would have the same wavelength restrictions. In
addition, a splitter is modeled by a connectivity matrix A_{mn} as
follows:

```
            Input    Output Port
            Port     #1 #2 #3 ...   #N
                     -----------------
     A =    #1       1  1  1  ...   1
```

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

3.4.3. Combiners

   An optical combiner is a device that combines the optical wavelengths
   carried by multiple input ports into a single multi-wavelength output
   port. The various ports may have different wavelength restrictions.
   It is generally the responsibility of those using the combiner to
   ensure that wavelength collision does not occur on the output port.
   The fixed connectivity matrix Amn for a combiner would look like:

```
              Input    Output Port
              Port     #1
                       ---
              #1:      1
              #2       1
        A =   #3       1
              ...      1
              #N       1
```

3.4.4. Fixed Optical Add/Drop Multiplexers

   A Fixed Optical Add/Drop Multiplexer can alter the course of an input
   wavelength in a preset way. In particular, a given wavelength (or
   waveband) from a line side input port would be dropped to a fixed
   "tributary" output port. Depending on the device's construction,
   that same wavelength may or may not also be sent out the line side
   output port. This is commonly referred to as a "drop and continue"
   operation. Tributary input ports ("add" ports) whose signals are
   combined with each other and other line side signals may also exist.

   In general, to represent the routing properties of an FOADM, it is
   necessary to have both a fixed connectivity matrix Amn, as previously
   discussed, and the precise wavelength restrictions for all input and
   output ports. From the wavelength restrictions on the tributary
   output ports, the wavelengths that have been selected can be derived.
   From the wavelength restrictions on the tributary input ports, it can
   be seen which wavelengths have been added to the line side output
   port. Finally, from the added wavelength information and the line
   side output wavelength restrictions, it can be inferred which
   wavelengths have been continued.

   To summarize, the modeling methodology introduced in Section 3.4.1,
   which consists 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].

3.5. Electro-Optical Systems

This section describes how Electro-Optical Systems (e.g., OEO
switches, wavelength converters, and regenerators) interact with the
WSON signal characteristics listed in Section 3.3.2. OEO switches,
wavelength converters, and regenerators all share a similar property:
they can be more or less "transparent" to an "optical signal"
depending on their functionality and/or implementation. Regenerators
have been fairly well characterized in this regard and hence their
properties can be described first.

3.5.1. Regenerators

The various approaches to regeneration are discussed in ITU-T
[G.872], Annex A. They map a number of functions into the so-called
1R, 2R, and 3R categories of regenerators as summarized in Table 1
below:

Table 1. Regenerator Functionality Mapped to General Regenerator
          Classes from [G.872]

1R	Equal amplification of all frequencies within the amplification bandwidth. There is no restriction upon information formats.
	Amplification with different gain for frequencies within the amplification bandwidth. This could be applied to both single-channel and multi-channel systems.
	Dispersion compensation (phase distortion). This analogue process can be applied in either single-channel or multi-channel systems.
2R	Any or all 1R functions. Noise suppression.
	Digital reshaping (Schmitt Trigger function) with no clock recovery. This is applicable to individual channels and can be used for different bitrates but is not transparent to line coding (modulation).
3R	Any or all 1R and 2R functions. Complete regeneration of the pulse shape including clock recovery and retiming within required jitter limits.

This table shows that 1R regenerators are generally independent of
signal modulation format (also known as line coding) but may work
over a limited range of wavelengths/frequencies. 2R regenerators are

generally applicable to a single digital stream and are dependent
upon modulation format (line coding) and, to a lesser extent, are
limited to a range of bitrates (but not a specific bitrate).
Finally, 3R regenerators apply to a single channel, are dependent
upon the modulation format, and are generally sensitive to the
bitrate of digital signal, i.e., either are designed to only handle a
specific bitrate or need to be programmed to accept and regenerate a
specific bitrate. In all these types of regenerators, the digital
bitstream contained within the optical or electrical signal is not
modified.

It is common for regenerators to modify the digital bitstream for
performance monitoring and fault management purposes. Synchronous
Optical Networking (SONET), Synchronous Digital Hierarchy (SDH), and
Interfaces for the Optical Transport Network [G.709] all have digital
signal "envelopes" designed to be used between "regenerators" (in
this case, 3R regenerators). In SONET, this is known as the
"section" signal; in SDH, this is known as the "regenerator section"
signal; and, in G.709, this is known as an OTUk. These signals
reserve a portion of their frame structure (known as overhead) for
use by regenerators. The nature of this overhead is summarized in
Table 2 below.

Table 2. SONET, SDH, and G.709 Regenerator-Related Overhead

Function	SONET/SDH Regenerator Section	G.709 OTUk
Signal Identifier	J0 (section trace)	Trail Trace Identifier (TTI)
Performance Monitoring	BIP-8 (B1)	BIP-8 (within SM)
Management Communications	D1-D3 bytes	GCC0 (general communications channel)
Fault Management	A1, A2 framing bytes	FAS (frame alignment signal), BDI (backward defect indication), BEI (backward error indication)
Forward Error Correction (FEC)	P1,Q1 bytes	OTUk FEC

Table 2 shows that frame alignment, signal identification, and FEC
are supported. By omission, Table 2 also shows that no switching or
multiplexing occurs at this layer. This is a significant
simplification for the control plane since control plane standards
require a multi-layer approach when there are multiple switching
layers but do not require the "layering" to provide the management
functions shown in Table 2. That is, many existing technologies
covered by GMPLS contain extra management-related layers that are
essentially ignored by the control plane (though not by the
management plane). Hence, the approach here is to include
regenerators and other devices at the WSON layer unless they provide
higher layer switching; then, a multi-layer or multi-region approach
[RFC5212] is called for. However, this can result in regenerators
having a dependence on the client signal type.

Hence, depending upon the regenerator technology, the constraints
listed in Table 3 may be imposed by a regenerator device:

Table 3. Regenerator Compatibility Constraints

Constraints	1R	2R	3R
Limited Wavelength Range	x	x	x
Modulation Type Restriction		x	x
Bitrate Range Restriction		x	x
Exact Bitrate Restriction			x
Client Signal Dependence			x

Note that the limited wavelength range constraint can be modeled for
GMPLS signaling with the Label Set defined in [RFC3471] and that the
modulation type restriction constraint includes FEC.

3.5.2. OEO Switches

A common place where OEO processing may take place is within WSON
switches that utilize (or contain) regenerators. This may be to
convert the signal to an electronic form for switching then reconvert
to an optical signal prior to output from the switch. Another common
technique is to add regenerators to restore signal quality either
before or after optical processing (switching). In the former case,
the regeneration is applied to adapt the signal to the switch fabric
regardless of whether or not it is needed from a signal-quality
perspective.

In either case, these optical switches have essentially the same
compatibility constraints as those described for regenerators in
Table 3.

3.6. Wavelength Converters

Wavelength converters take an input optical signal at one wavelength
and emit an equivalent content optical signal at another wavelength
on output. There are multiple approaches to building wavelength
converters. One approach is based on OEO conversion with fixed or
tunable optics on output. This approach can be dependent upon the
signal rate and format; that is, this is basically an electrical
regenerator combined with a laser/receiver. Hence, this type of
wavelength converter has signal-processing restrictions that are
essentially the same as those described for regenerators in Table 3
of Section 3.5.1.

Another 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 fixed or tunable optics. In this case, there are typically multiple converters available since each use of an OEO switch can be thought of as a potential wavelength converter.

2. Wavelength conversion associated with ROADMs/OXCs. In this case, there may be a limited pool of wavelength converters 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, there may be a limited amount of conversion. Also, the conversion may be used as part of optical path routing.

Based on the above considerations, wavelength converters are modeled 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 input 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, they can be associated with input ports.

3. Wavelength converters have range restrictions that are either independent or dependent upon the input wavelength.

In WSONs where wavelength converters are sparse, an optical path may 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 input to the wavelength converter would be different from the lambda coming back from the wavelength converter.

A model for an individual OEO wavelength converter would consist of:

o Input lambda or frequency range

o Output lambda or frequency range

3.6.1. Wavelength Converter Pool Modeling

A WSON node may include multiple wavelength converters. These are
usually arranged into some type of pool to promote resource sharing.
There are a number of different approaches used in the design of
switches with converter pools. However, from the point of view of
path computation, it is necessary to know the following:

1. The nodes that support wavelength conversion

2. The accessibility and availability of a wavelength converter to
    convert from a given input wavelength on a particular input port
    to a desired output wavelength on a particular output port

3. Limitations on the types of signals that can be converted and the
    conversions that can be performed

To model point 2 above, a technique similar to that used to model
ROADMs and optical switches can be used, i.e., matrices to indicate
possible connectivity along with wavelength constraints for
links/ports. Since wavelength converters are considered a scarce
resource, it is desirable to include, at a minimum, the usage state
of individual wavelength converters in the pool.

A three stage model is used as shown schematically in Figure 3. This
model represents N input ports (fibers), P wavelength converters, and
M output ports (fibers). Since not all input ports can necessarily
reach the converter pool, the model starts with a wavelength pool
input matrix $WI(i,p) = \{0,1\}$, where input port i can potentially
reach wavelength converter p.

Since not all wavelengths can necessarily reach all the converters or
the converters may have a limited input wavelength range, there is a
set of input port constraints for each wavelength converter.
Currently, it is assumed that a wavelength converter can only take a
single wavelength on input. Each wavelength converter input port
constraint can be modeled via a wavelength set mechanism.

Next, there is a state vector $WC(j) = \{0,1\}$ dependent upon whether
wavelength converter j in the pool is in use. This is the only state
kept in the converter pool model. This state is not necessary for
modeling "fixed" transponder system, i.e., systems where there is no

sharing. In addition, this state information may be encoded in a
much more compact form depending on the overall connectivity
structure [Gen-Encode].

After that, a set of wavelength converter output wavelength
constraints is used. These constraints indicate what wavelengths a
particular wavelength converter can generate or are restricted to
generating due to internal switch structure.

Finally, a wavelength pool output matrix $WE(p,k) = \{0,1\}$ indicates
whether the output from wavelength converter p can reach output port
k. Examples of this method being used to model wavelength converter
pools for several switch architectures are given in [Gen-Encode].

```
   I1   +-------------+                            +-------------+ E1
   ----->|            |         +---------+        |             | ----->
   I2   |            +------+ WC #1  +-------+ |             | E2
   ----->|            |         +---------+        |             | ----->
        | Wavelength  |                            | Wavelength  |
        | Converter   |         +---------+        | Converter   |
        | Pool        +------+ WC #2  +-------+ | Pool        |
        |            |         +---------+        |             |
        | Input       |                           | Output      |
        | Connection  |            .              | Connection  |
        | Matrix      |            .              | Matrix      |
        |            |            .              |             |
   IN   |            |         +---------+        |             | EM
   ----->|            +------+ WC #P  +-------+ |             | ----->
        |            |  ^      +---------+   ^   |             |
        +-------------+  |                   |   +-------------+
                         |                   |
                         |                   |
                         |                   |

            Input wavelength     Output wavelength
            constraints for      constraints for
            each converter       each converter
```
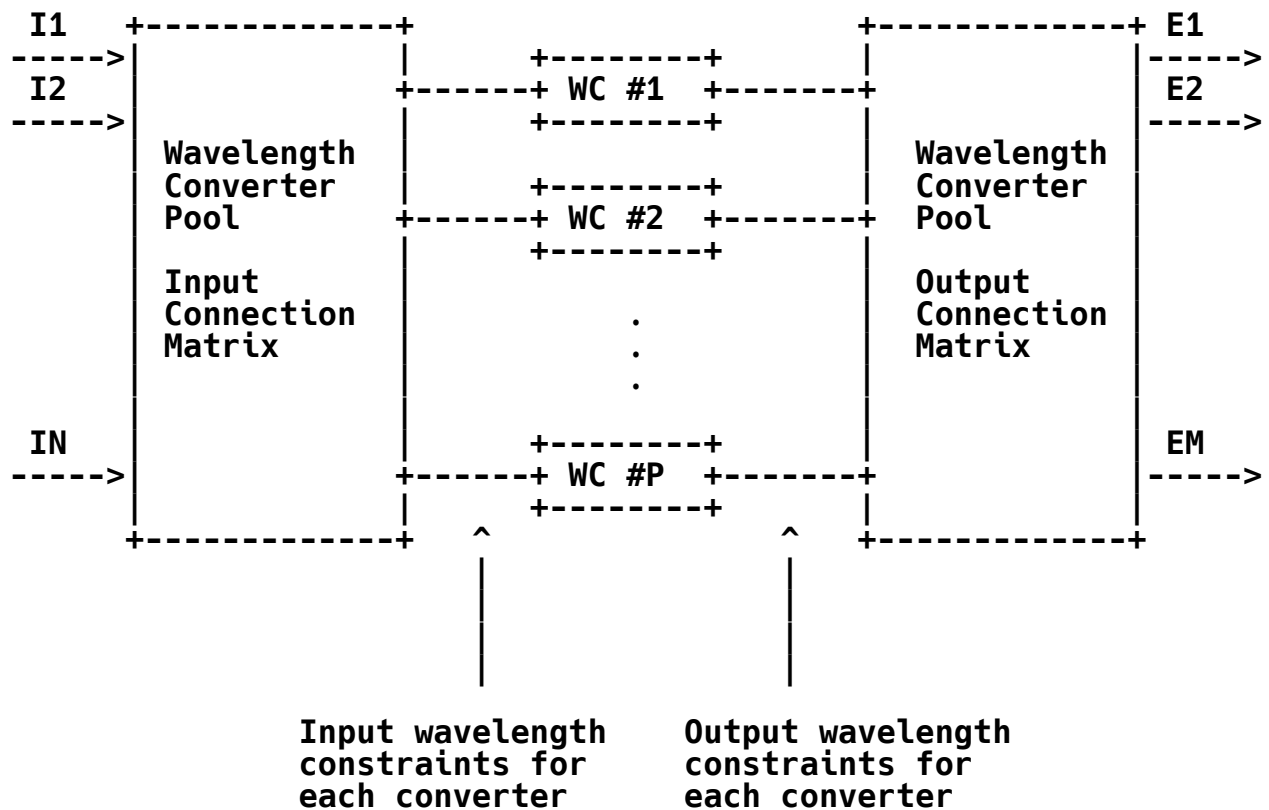
      Figure 3. Schematic Diagram of Wavelength Converter Pool Model

Figure 4 shows a simple optical switch in a four-wavelength DWDM
system sharing wavelength converters in a general shared "per-node"
fashion.

```
                +-----------+  _____
                |           |  ------------------------------->
                |           | ------------------------------->|
                |           | ------------------------------->| C
        /|      |           | ------------------------------->| o   E1
   I1  /D+--->  |           |                                 | m
       + e+--->  |           |                                 | b
       + M|      | Optical   |                                 | i ====>
 ====>| u+--->  | Switch    |                                 | n
       \x+--->  |           |    +-----------+ +----+ -->     | e
        \|      |           |    | WC Pool   | |O  S| -->     | r
                |           |    | +-----+   | |p  w|         +------+
                |           +-----+-->|WC #1|--+-->|t  i|
                |           |    | +-----+   | |i  t|         +------+
                |           |    |           | |c  c| -->     | C
                |           |    |           | |a  h| -->     | o   E2
        /|      |           |    | +-----+   | |l   |         | m
   I2  /D+--->  |           +-----+-->|WC #2|--+-->|    | -->  | b
       + e+--->  |           |    | +-----+   | |    | -->  | i ====>
 ====>| M|      |           |    +-----------+ +----+         | n
       + u+--->  |           |                                 | e
       \x+--->  |           | ------------------------------->| r
        \|      |           | ------------------------------->|
                |           | ------------------------------->|
                |_____| ------------------------------->|
                +-----------+                                 +------+
```
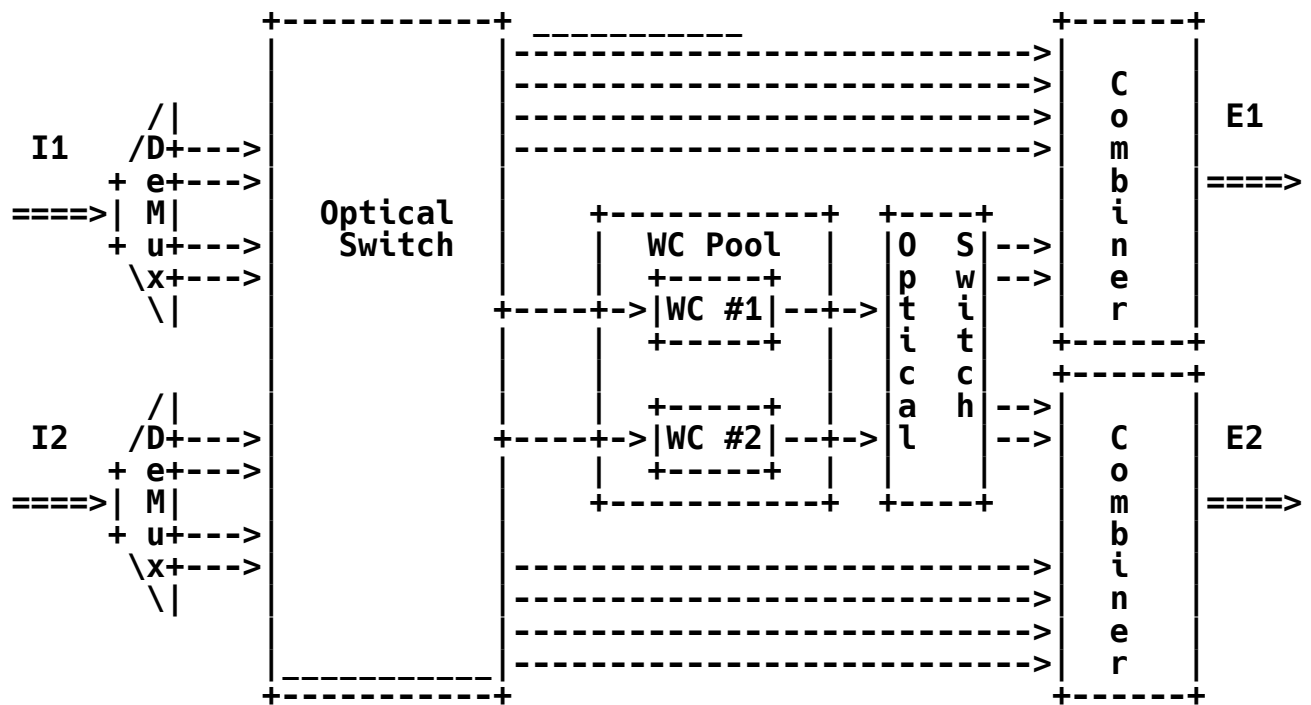
   Figure 4.   An Optical Switch Featuring a Shared Per-Node Wavelength
               Converter Pool Architecture

In this case, the input and output pool matrices are simply:

```
         +-----+          +-----+
         | 1 1 |          | 1 1 |
   WI =  |     |  ,   WE = |     |
         | 1 1 |          | 1 1 |
         +-----+          +-----+
```

Figure 5 shows a different wavelength pool architecture known as
"shared per fiber". In this case, the input and output pool matrices
are simply:

```
         +-----+          +-----+
         | 1 1 |          | 1 0 |
   WI =  |     |  ,   WE = |     |
         | 1 1 |          | 0 1 |
         +-----+          +-----+
```

```
          +-----------+   +----------+
          |           |   ------------------------------->|C      |
          |           |   ------------------------------->|o      | E1
    /|    |           |   ------------------------------->|m      |
 I1 /D+--->|           |   ------------------------------->|b      |
   + e+--->|           |                                   |i      | ====>
====>| M|  | Optical   |                                   |n      |
   + u+--->| Switch    |   +-----------+                   |e      |
   \x+--->|           |   | WC Pool   |                   |r      |
    \|    |           |   | +-----+   |                   |       |
          |           +-----+-->|WC #1|--+----------->|       |
          |           |   | +-----+   |               +------+
          |           |   |           |
          |           |   | +-----+   |               +------+
    /|    |           |   | +-----+   |               |C      |
 I2 /D+--->|           +-----+-->|WC #2|--+----------->|o      | E2
   + e+--->|           |   | +-----+   |               |m      |
====>| M|  |           |   +-----------+               |b      | ====>
   + u+--->|           |                               |i      |
   \x+--->|           |   ------------------------------->|n      |
    \|    |           |   ------------------------------->|e      |
          |_____|   ------------------------------->|r      |
          +-----------+   ------------------------------->+------+
```
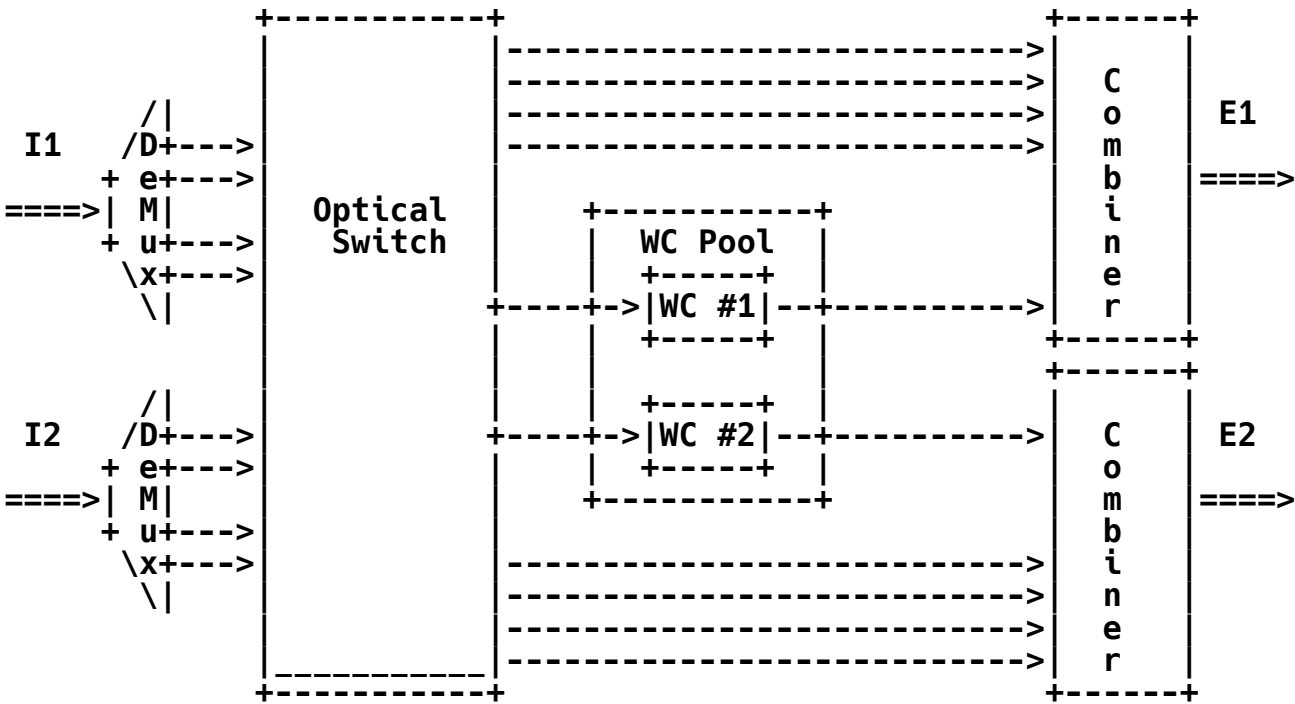
       Figure 5.   An Optical Switch Featuring a Shared Per-Fiber Wavelength
                   Converter Pool Architecture

3.7.   Characterizing Electro-Optical Network Elements

    In this section, electro-optical WSON network elements are
    characterized by the three key functional components: input
    constraints, output constraints, and processing capabilities.

```
                        WSON Network Element
       WSON Signal      +----------------------+     WSON Signal
                        |     |      |      |   |
       --------------->  |     |      |      |   |   ----------------->
                        |     |      |      |   |
                        +----------------------+
                        <-----> <-------> <----->

                         Input   Processing Output
```

                    Figure 6.   WSON Network Element

3.7.1. Input Constraints

   Sections 3.5 and 3.6 discuss the basic properties of regenerators,
   OEO switches, and wavelength converters. From these, the following
   possible types of input constraints and properties are derived:

   1. Acceptable modulation formats

   2. Client signal (G-PID) restrictions

   3. Bitrate restrictions

   4. FEC coding restrictions

   5. Configurability: (a) none, (b) self-configuring, (c) required

   These constraints are represented via simple lists. Note that the
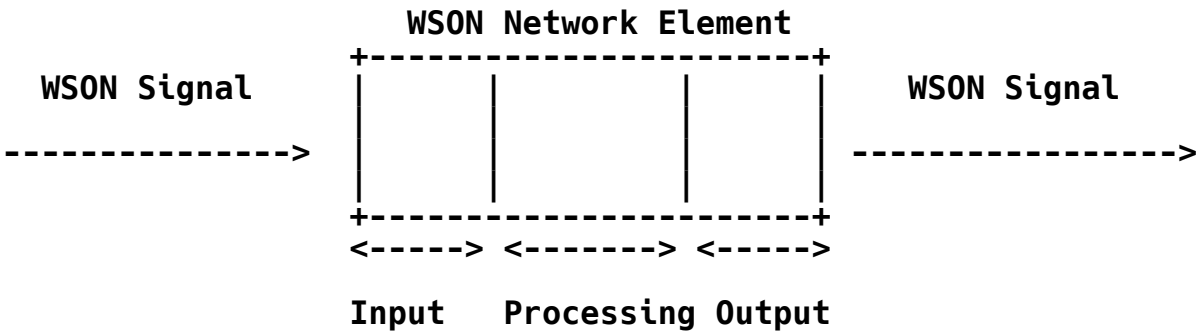   device may need to be "provisioned" via signaling or some other means
   to accept signals with some attributes versus others. In other
   cases, the devices may be relatively transparent to some attributes,
   e.g., a 2R regenerator to bitrate. Finally, some devices may be able
   to auto-detect some attributes and configure themselves, e.g., a 3R
   regenerator with bitrate detection mechanisms and flexible phase
   locking circuitry. To account for these different cases, item 5 has
   been added, which describes the device's configurability.

   Note that such input constraints also apply to the termination of the
   WSON signal.

3.7.2. Output Constraints

   None of the network elements considered here modifies either the
   bitrate or the basic type of the client signal. However, they may
   modify the modulation format or the FEC code. Typically, the
   following types of output constraints are seen:

   1. Output modulation is the same as input modulation (default)

   2. A limited set of output modulations is available

   3. Output FEC is the same as input FEC code (default)

   4. A limited set of output FEC codes is available

   Note that in cases 2 and 4 above, where there is more than one choice
   in the output modulation or FEC code, the network element will need
   to be configured on a per-LSP basis as to which choice to use.

3.7.3. Processing Capabilities

A general WSON network element (NE) can perform a number of signal processing functions including:

(A) Regeneration (possibly different types)

(B) Fault and performance monitoring

(C) Wavelength conversion

(D) Switching

An NE may or may not have the ability to perform regeneration (of one of the types previously discussed). In addition, some nodes may have limited regeneration capability, i.e., a shared pool, which may be applied to selected signals traversing the NE. Hence, to describe the regeneration capability of a link or node, it is necessary to have, at a minimum:

1. Regeneration capability: (a) fixed, (b) selective, (c) none

2. Regeneration type: 1R, 2R, 3R

3. Regeneration pool properties for the case of selective regeneration (input and output restrictions, availability)

Note that the properties of shared regenerator pools would be essentially the same as that of wavelength converter pools modeled in Section 3.6.1.

Item B (fault and performance monitoring) is typically outside the scope of the control plane. However, when the operations are to be performed on an LSP basis or on part of an LSP, the control plane can be of assistance in their configuration. Per-LSP, per-node, and fault and performance monitoring examples include setting up a "section trace" (a regenerator overhead identifier) between two nodes or intermediate optical performance monitoring at selected nodes along a path.

4. Routing and Wavelength Assignment and the Control Plane

From a control plane perspective, a wavelength-convertible network with full wavelength-conversion capability at each node can be controlled much like a packet MPLS-labeled network or a circuit-switched Time Division Multiplexing (TDM) network with full-time slot interchange capability is controlled. In this case, the path

selection process needs to identify the Traffic Engineered (TE) links
to be used by an optical path, and wavelength assignment can be made
on a hop-by-hop basis.

However, in the case of an optical network without wavelength
converters, an optical path needs to be routed from source to
destination and must use a single wavelength that is available along
that path without "colliding" with a wavelength used by any other
optical path that may share an optical fiber. This is sometimes
referred to as a "wavelength continuity constraint".

In the general case of limited or no wavelength converters, the
computation of both the links and wavelengths is known as RWA.

The inputs to basic RWA are the requested optical path's source and
destination, the network topology, the locations and capabilities of
any wavelength converters, and the wavelengths available on each
optical link. The output from an algorithm providing RWA is an
explicit route through ROADMs, a wavelength for 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 the choice of a specific RWA algorithm is out
of the scope of this document. However, there are a number of
different approaches to dealing with RWA algorithms that can affect
the division of effort between path computation/routing and
signaling.

4.1. Architectural Approaches to RWA

Two general computational approaches are taken to performing RWA.
Some algorithms utilize a two-step procedure of path selection
followed by wavelength assignment, and others perform RWA in a
combined fashion.

In the following sections, 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. The
approaches are provided for reference purposes only, and other
approaches are possible.

4.1.1. Combined RWA (R&WA)

In this case, a unique entity is in charge of performing routing and
wavelength assignment. This approach relies on a sufficient
knowledge of network topology, of available network resources, and of

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

   Such a computational entity could reside in two different places:

   o In a PCE that maintains a complete and updated view of network
      state and provides path computation services to nodes

   o In an ingress node, in which case all nodes have the R&WA
      functionality and 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, one entity performs routing while a second performs
   wavelength assignment. The first entity furnishes one or more paths
   to the second entity, which will perform wavelength assignment and
   final path selection.

   The separation of the entities computing the path and the wavelength
   assignment constrains the class of RWA algorithms that may be
   implemented. Although it may seem that algorithms optimizing a joint
   usage of the physical and wavelength 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. Hence, while there is no guarantee that the selected
   final route and wavelength offer the optimal solution, reasonable
   optimization can be performed by allowing multiple routes to pass to
   the wavelength selection process.

   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's available
   resources and specific network node capabilities.

4.1.3. Routing and Distributed WA (R+DWA)

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

   As currently specified, the GMPLS protocol suite signaling protocol
   can accommodate such an approach. GMPLS, per [RFC3471], includes
   support for the communication of the set of labels (wavelengths) that

may be used between nodes via a Label Set. When conversion is not
performed at an intermediate node, a hop generates the Label Set it
sends to the next hop based on the intersection of the Label Set
received from the previous hop and the wavelengths available on the
node's switch and ongoing interface. The generation of the outgoing
Label Set 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 node selects one
label in the Label Set that it received; additionally, the node can
apply local policy during label selection. GMPLS also provides
support for the signaling of bidirectional optical paths.

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

This solution may be facilitated via signaling extensions that ease
its functioning and possibly enhance its performance with respect to
blocking probability. Note that this approach requires less
information dissemination than the other techniques described.

The first entity may be a PCE or the ingress node of the LSP.

4.2. Conveying Information Needed by RWA

The previous sections have characterized WSONs and optical path
requests. In particular, high-level models of the information used
by RWA process were presented. This information can be viewed as
either relatively static, i.e., changing with hardware changes
(including possibly failures), or relatively dynamic, i.e., those
that can change with optical path provisioning. The time requirement
in which an entity involved in RWA process needs to be 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, the following:

o Existing control plane protocols, i.e., GMPLS routing and
   signaling. Note that routing protocols can be used to convey both
   static and dynamic information.

o Management protocols such as NetConf, SNMPv3, and CORBA.

o Methods to access configuration and status information such as a
   command line interface (CLI).

o Directory services and accompanying protocols. These are
   typically used for the dissemination of relatively static
   information. Directory services are not suited to manage
   information in dynamic and fluid environments.

o Other techniques for dynamic information, e.g., sending
   information directly from NEs to PCEs to avoid flooding. This
   would be useful if the number of PCEs is significantly less than
   the number of WSON NEs. There may be other ways to limit flooding
   to "interested" NEs.

Possible mechanisms to improve scaling of dynamic information
include:

o Tailoring message content to WSON, e.g., the use of wavelength
   ranges or wavelength occupation bit maps

o Utilizing incremental updates if feasible

5. Modeling Examples and Control Plane Use Cases

This section provides examples of the fixed and switched optical node
and wavelength constraint models of Section 3 and use cases for WSON
control plane path computation, establishment, rerouting, and
optimization.

5.1. Network Modeling for GMPLS/PCE Control

Consider a network containing three routers (R1 through R3), eight
WSON nodes (N1 through N8), 18 links (L1 through L18), and one OEO
converter (O1) in a topology shown in Figure 7.

```
                        +--+      +--+                  +--+     +--------+
                     +-L3-+N2+-L5-+  +--------L12--+N6+--L15--+   N8    +
                        |  +--+    |N4+-L8---+      +--+     ++--+---++
                        |          +-L9--+|               |    L17 L18
         +--+       +-+-+          ++-+   ||              |    |   |
         ++-L1--+       |          |     ++++            +----L16---+    |   |
         |R1|   ++-L2--+ | N1|          |L7   |R2|              |    ++---++
         |  ++-L2--+  |   |          |     ++-+              +    R3 |
         +--+       +-+-+          |                          +-----+
            |          |  +--+    ++-+         |
                     +-L4-+N3+-L6-+N5+-L10-+          ++----+
                        +--+    |  +-------L11--+ N7   +
                                +--+            ++---++
                                                |    |
                                               L13 L14
                                                |    |
                                               ++-+  |
                                               |O1+-+
                                               +--+
```
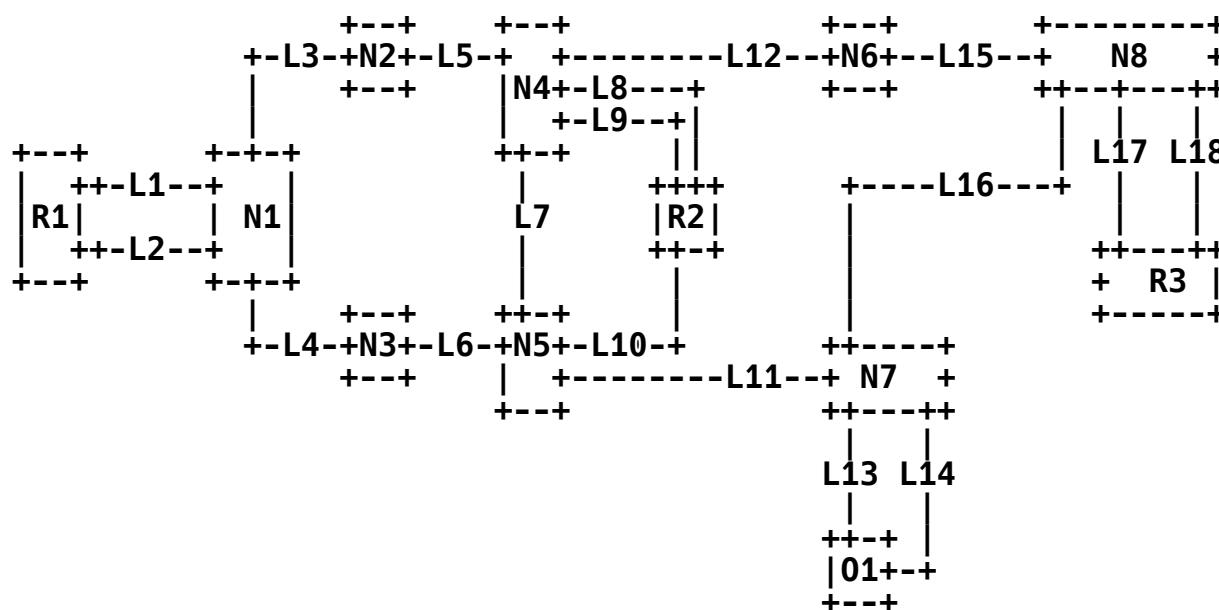
          Figure 7.   Routers and WSON Nodes in a GMPLS and PCE Environment

5.1.1. Describing the WSON Nodes

   The eight WSON nodes described in Figure 7 have the following
   properties:

   o Nodes N1, N2, and N3 have FOADMs installed and can therefore only
      access a static and pre-defined set of wavelengths.

   o All other nodes contain ROADMs and can therefore access all
      wavelengths.

   o Nodes N4, N5, N7, and N8 are multi-degree nodes, allowing any
      wavelength to be optically switched between any of the links.
      Note, however, that this does not automatically apply to
      wavelengths that are being added or dropped at the particular
      node.

   o Node N4 is an exception to that: this node can switch any
      wavelength from its add/drop ports to any of its output links (L5,
      L7, and L12 in this case).

   o The links from the routers are only able to carry one wavelength,
      with the exception of links L8 and L9, which are capable to
      add/drop any wavelength.

o Node N7 contains an OEO transponder (O1) connected to the node via
   links L13 and L14. That transponder operates in 3R mode and does
   not change the wavelength of the signal. Assume that it can
   regenerate any of the client signals but only for a specific
   wavelength.

Given the above restrictions, the node information for the eight
nodes can be expressed as follows (where ID = identifier, SCM =
switched connectivity matrix, and FCM = fixed connectivity matrix):

```
+ID+SCM                          +FCM                               +
|   |  |L1 |L2 |L3 |L4 |        |  |L1 |L2 |L3 |L4 |               |
|   |L1|0  |0  |0  |0  |        |L1|0  |0  |1  |0  |               |
|   |L2|0  |0  |0  |0  |        |L2|0  |0  |0  |1  |               |
|N1 |L3|0  |0  |0  |0  |        |L3|1  |0  |0  |1  |               |
|   |L4|0  |0  |0  |0  |        |L4|0  |1  |1  |0  |               |
+---+--+---+---+---+---+----+----+--+---+---+---+---+----+----+----+
|   |  |L3 |L5 |   |   |        |  |L3 |L5 |   |   |               |
|N2 |L3|0  |0  |   |   |        |L3|0  |1  |   |   |               |
|   |L5|0  |0  |   |   |        |L5|1  |0  |   |   |               |
+---+--+---+---+---+---+----+----+--+---+---+---+---+----+----+----+
|   |  |L4 |L6 |   |   |        |  |L4 |L6 |   |   |               |
|N3 |L4|0  |0  |   |   |        |L4|0  |1  |   |   |               |
|   |L6|0  |0  |   |   |        |L6|1  |0  |   |   |               |
+---+--+---+---+---+---+----+----+--+---+---+---+---+----+----+----+
|   |  |L5 |L7 |L8 |L9 |L12 |  |L5 |L7 |L8 |L9 |L12 |
|   |L5|0  |1  |1  |1  |1   |L5|0  |0  |0  |0  |0   |
|N4 |L7|1  |0  |1  |1  |1   |L7|0  |0  |0  |0  |0   |
|   |L8|1  |1  |0  |1  |1   |L8|0  |0  |0  |0  |0   |
|   |L9|1  |1  |1  |0  |1   |L9|0  |0  |0  |0  |0   |
|   |L12|1 |1  |1  |1  |0   |L12|0 |0  |0  |0  |0   |
+---+--+---+---+---+---+----+----+--+---+---+---+---+----+----+----+
|   |  |L6 |L7 |L10|L11|        |  |L6 |L7 |L10|L11|               |
|   |L6|0  |1  |0  |1  |        |L6|0  |0  |1  |0  |               |
|N5 |L7|1  |0  |0  |1  |        |L7|0  |0  |0  |0  |               |
|   |L10|0 |0  |0  |0  |        |L10|1 |0  |0  |0  |               |
|   |L11|1 |1  |0  |0  |        |L11|0 |0  |0  |0  |               |
+---+--+---+---+---+---+----+----+--+---+---+---+---+----+----+----+
|   |  |L12|L15|   |   |        |  |L12|L15|   |   |               |
|N6 |L12|0 |1  |   |   |        |L12|0 |0  |   |   |               |
|   |L15|1 |0  |   |   |        |L15|0 |0  |   |   |               |
+---+--+---+---+---+---+----+----+--+---+---+---+---+----+----+----+
|   |  |L11|L13|L14|L16|        |  |L11|L13|L14|L16|               |
|   |L11|0 |1  |0  |1  |        |L11|0 |0  |0  |0  |               |
|N7 |L13|1 |0  |0  |0  |        |L13|0 |0  |1  |0  |               |
|   |L14|0 |0  |0  |1  |        |L14|0 |1  |0  |0  |               |
|   |L16|1 |0  |1  |0  |        |L16|0 |0  |1  |0  |               |
+---+--+---+---+---+---+----+----+--+---+---+---+---+----+----+----+
|   |  |L15|L16|L17|L18|        |  |L15|L16|L17|L18|               |
|   |L15|0 |1  |0  |0  |        |L15|0 |0  |0  |1  |               |
|N8 |L16|1 |0  |0  |0  |        |L16|0 |0  |1  |0  |               |
|   |L17|0 |0  |0  |0  |        |L17|0 |1  |0  |0  |               |
|   |L18|0 |0  |0  |0  |        |L18|1 |0  |1  |0  |               |
+---+--+---+---+---+---+----+----+--+---+---+---+---+----+----+----+
```

5.1.2. Describing the Links

   For the following discussion, some simplifying assumptions are made:

   o It is assumed that the WSON node supports a total of four
      wavelengths, designated WL1 through WL4.

   o It is assumed that the impairment feasibility of a path or path
      segment is independent from the wavelength chosen.

   For the discussion of RWA operation, to build LSPs between two
   routers, the wavelength constraints on the links between the routers
   and the WSON nodes as well as the connectivity matrix of these links
   need to be specified:

```
+Link+WLs supported      +Possible output links+
| L1 | WL1             | L3                   |
+----+-----------------+----------------------+
| L2 | WL2             | L4                   |
+----+-----------------+----------------------+
| L8 | WL1 WL2 WL3 WL4 | L5 L7 L12            |
+----+-----------------+----------------------+
| L9 | WL1 WL2 WL3 WL4 | L5 L7 L12            |
+----+-----------------+----------------------+
| L10| WL2             | L6                   |
+----+-----------------+----------------------+
| L13| WL1 WL2 WL3 WL4 | L11 L14              |
+----+-----------------+----------------------+
| L14| WL1 WL2 WL3 WL4 | L13 L16              |
+----+-----------------+----------------------+
| L17| WL2             | L16                  |
+----+-----------------+----------------------+
| L18| WL1             | L15                  |
+----+-----------------+----------------------+
```

   Note that the possible output links for the links connecting to the
   routers is inferred from the switched connectivity matrix and the
   fixed connectivity matrix of the Nodes N1 through N8 and is shown
   here for convenience; that is, this information does not need to be
   repeated.

5.2. RWA Path Computation and Establishment

   The calculation of optical impairment feasible routes is outside the
   scope of this document. In general, optical impairment feasible
   routes serve as an input to an RWA algorithm.

For the example use case shown here, assume the following feasible
routes:

```
+Endpoint 1+Endpoint 2+Feasible Route         +
|    R1     | R2        | L1  L3  L5  L8              |
|    R1     | R2        | L1  L3  L5  L9              |
|    R1     | R2        | L2  L4  L6  L7  L8          |
|    R1     | R2        | L2  L4  L6  L7  L9          |
|    R1     | R2        | L2  L4  L6  L10             |
|    R1     | R3        | L1  L3  L5  L12 L15 L18     |
|    R1     | N7        | L2  L4  L6  L11             |
|    N7     | R3        | L16 L17                     |
|    N7     | R2        | L16 L15 L12 L9              |
|    R2     | R3        | L8  L12 L15 L18             |
|    R2     | R3        | L8  L7  L11 L16 L17         |
|    R2     | R3        | L9  L12 L15 L18             |
|    R2     | R3        | L9  L7  L11 L16 L17         |
```

Given a request to establish an LSP between R1 and R2, an RWA
algorithm finds the following possible solutions:

```
+WL   + Path          +
| WL1| L1 L3 L5 L8      |
| WL1| L1 L3 L5 L9      |
| WL2| L2 L4 L6 L7 L8|
| WL2| L2 L4 L6 L7 L9|
| WL2| L2 L4 L6 L10    |
```

Assume now that an RWA algorithm yields WL1 and the path L1 L3 L5 L8
for the requested LSP.

Next, another LSP is signaled from R1 to R2. Given the established
LSP using WL1, the following table shows the available paths:

```
+WL   + Path          +
| WL2| L2 L4 L6 L7 L9|
| WL2| L2 L4 L6 L10    |
```

Assume now that an RWA algorithm yields WL2 and the path L2 L4 L6 L7
L9 for the establishment of the new LSP.

An LSP request -- this time from R2 to R3 -- cannot be fulfilled
since the four possible paths (starting at L8 and L9) are already in
use.

5.3. Resource Optimization

The preceding example gives rise to another use case: the
optimization of network resources. Optimization can be achieved on a
number of layers (e.g., through electrical or optical multiplexing of
client signals) or by re-optimizing the solutions found by an RWA
algorithm.

Given the above example again, assume that an RWA algorithm should
identify a path between R2 and R3. The only possible path to reach
R3 from R2 needs to use L9. L9, however, is blocked by one of the
LSPs from R1.

5.4. Support for Rerouting

It is also envisioned that the extensions to GMPLS and PCE support
rerouting of wavelengths in case of failures.

For this discussion, assume that the only two LSPs in use in the
system are:

LSP1: WL1 L1 L3 L5 L8

LSP2: WL2 L2 L4 L6 L7 L9

Furthermore, assume that the L5 fails. An RWA algorithm can now
compute and establish the following alternate path:

R1 -> N7 -> R2

Level 3 regeneration will take place at N7, so that the complete path
looks like this:

R1 -> L2 L4 L6 L11 L13 -> O1 -> L14 L16 L15 L12 L9 -> R2

5.5. Electro-Optical Networking Scenarios

In the following subsections, various networking scenarios are
considered involving regenerators, OEO switches, and wavelength
converters. These scenarios can be grouped roughly by type and
number of extensions to the GMPLS control plane that would be
required.

5.5.1. Fixed Regeneration Points

In the simplest networking scenario involving regenerators, regeneration is associated with a WDM link or an entire node and is not optional; that is, all signals traversing the link or node will be regenerated. This includes OEO switches since they provide regeneration on every port.

There may be input constraints and output constraints on the regenerators. Hence, the path selection process will need to know the regenerator constraints from routing or other means so that it can choose a compatible path. For impairment-aware routing and wavelength assignment (IA-RWA), the path selection process will also need to know which links/nodes provide regeneration. Even for "regular" RWA, this regeneration information is useful since wavelength converters typically perform regeneration, and the wavelength continuity constraint can be relaxed at such a point.

Signaling does not need to be enhanced to include this scenario since there are no reconfigurable regenerator options on input, output, or processing.

5.5.2. Shared Regeneration Pools

In this scenario, there are nodes with shared regenerator pools within the network in addition to the fixed regenerators of the previous scenario. These regenerators are shared within a node and their application to a signal is optional. There are no reconfigurable options on either input or output. The only processing option is to "regenerate" a particular signal or not.

In this case, regenerator information is used in path computation to select a path that ensures signal compatibility and IA-RWA criteria.

To set up an LSP that utilizes a regenerator from a node with a shared regenerator pool, it is necessary to indicate that regeneration is to take place at that particular node along the signal path. Such a capability does not currently exist in GMPLS signaling.

5.5.3. Reconfigurable Regenerators

This scenario is concerned with regenerators that require configuration prior to use on an optical signal. As discussed previously, this could be due to a regenerator that must be configured to accept signals with different characteristics, for regenerators with a selection of output attributes, or for regenerators with additional optional processing capabilities.

As in the previous scenarios, it is necessary to have information
concerning regenerator properties for selection of compatible paths
and for IA-RWA computations. In addition, during LSP setup, it is
necessary to be able to configure regenerator options at a particular
node along the path. Such a capability does not currently exist in
GMPLS signaling.

5.5.4. Relation to Translucent Networks

Networks that contain both transparent network elements such as
Reconfigurable Optical Add/Drop Multiplexers (ROADMs) and electro-
optical network elements such as regenerators or OEO switches are
frequently referred to as translucent optical networks.

Three main types of translucent optical networks have been discussed:

1. Transparent "islands" surrounded by regenerators. This is
    frequently seen when transitioning from a metro optical
    subnetwork to a long-haul optical subnetwork.

2. Mostly transparent networks with a limited number of OEO
    ("opaque") nodes strategically placed. This takes advantage of
    the inherent regeneration capabilities of OEO switches. In the
    planning of such networks, one has to determine the optimal
    placement of the OEO switches.

3. Mostly transparent networks with a limited number of optical
    switching nodes with "shared regenerator pools" that can be
    optionally applied to signals passing through these switches.
    These switches are sometimes called translucent nodes.

All three types of translucent networks fit within the networking
scenarios of Sections 5.5.1 and 5.5.2. Hence, they can be
accommodated by the GMPLS extensions envisioned in this document.

6. GMPLS and PCE Implications

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

6.1. 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 in distributed
   wavelength assignment processes, which are discussed below.

6.1.1. 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, a mapping like the one described in [RFC6205] provides
   fixed mapping for communication between PCE and WSON PCCs.

6.1.2. WSON Signals and Network Element Processing

   As discussed in Section 3.3.2, a WSON signal at any point along its
   path can be characterized by the (a) modulation format, (b) FEC, (c)
   wavelength, (d) bitrate, and (e) G-PID.

   Currently, G-PID, wavelength (via labels), and bitrate (via bandwidth
   encoding) are supported in [RFC3471] and [RFC3473]. These RFCs can
   accommodate the wavelength changing at any node along the LSP and can
   thus provide explicit control of wavelength converters.

   In the fixed regeneration point scenario described in Section 5.5.1,
   no enhancements are required to signaling since there are no
   additional configuration options for the LSP at a node.

   In the case of shared regeneration pools described in Section 5.5.2,
   it is necessary to indicate to a node that it should perform
   regeneration on a particular signal. Viewed another way, for an LSP,
   it is desirable to specify that certain nodes along the path perform
   regeneration. Such a capability does not currently exist in GMPLS
   signaling.

   The case of reconfigurable regenerators described in Section 5.5.3 is
   very similar to the previous except that now there are potentially
   many more items that can be configured on a per-node basis for an
   LSP.

   Note that the techniques of [RFC5420] that allow for additional LSP
   attributes and their recording in a Record Route Object (RRO) could
   be extended to allow for additional LSP attributes in an Explicit
   Route Object (ERO). This could allow one to indicate where optional

3R regeneration should take place along a path, any modification of
LSP attributes such as modulation format, or any enhance processing
such as performance monitoring.

6.1.3. Combined RWA/Separate Routing WA support

In either the combined RWA case or the separate routing WA case, 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 used to indicate the wavelength to be used at a
particular node. In case the local label map approach is used, the
label subobject entry in the ERO has to be interpreted appropriately.

6.1.4. Distributed Wavelength Assignment: Unidirectional, No Converters

GMPLS signaling for a unidirectional optical path LSP allows for the
use of a Label Set object in the Resource Reservation Protocol -
Traffic Engineering (RSVP-TE) path message. 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 lambdas being
known to the destination, which can then use a wavelength selection
algorithm to choose a lambda.

6.1.5. Distributed Wavelength Assignment: Unidirectional, Limited
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 that is obtained via the intersection of the
incoming Label Set and the output 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 is processed. The node will pass on an enlarged label
set reflecting only the limitations of the wavelength converter and
the output link. The record route option in RSVP-TE signaling can be
used to show where wavelength conversion has taken place.

6.1.6. Distributed Wavelength Assignment: Bidirectional, No Converters

There are cases of a bidirectional optical path that require the use
of the same lambda in both directions. The above procedure can be
used to determine the available bidirectional lambda set if it is

interpreted that the available Label Set is available in both
directions. According to [RFC3471], Section 4.1, the setup of
bidirectional LSPs is indicated by the presence of an upstream label
in the path message.

However, until the intersection of the available Label Sets is
determined along the path and at the destination node, the upstream
label information may not be correct. This case can be supported
using current GMPLS mechanisms but may not be as efficient as an
optimized bidirectional single-label allocation mechanism.

6.2. Implications for GMPLS Routing

GMPLS routing [RFC4202] currently defines an interface capability
descriptor for "Lambda Switch Capable" (LSC) that can be used to
describe the interfaces on a ROADM or other type of wavelength
selective switch. In addition to the topology information typically
conveyed via an Interior Gateway Protocol (IGP), it would be
necessary to convey the following subsystem properties to minimally
characterize a WSON:

1. WDM link properties (allowed wavelengths)

2. Optical 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)

This information is modeled in detail in [WSON-Info], and a compact
encoding is given in [WSON-Encode].

6.2.1. Electro-Optical Element Signal Compatibility

In network scenarios where signal compatibility is a concern, it is
necessary to add parameters to our existing node and link models to
take into account electro-optical input constraints, output
constraints, and the signal-processing capabilities of an NE in path
computations.

Input constraints:

1. Permitted optical tributary signal classes: A list of optical
    tributary signal classes that can be processed by this network
    element or carried over this link (configuration type)

2. Acceptable FEC codes (configuration type)

3. Acceptable bitrate set: a list of specific bitrates or bitrate
    ranges that the device can accommodate. Coarse bitrate info is
    included with the optical tributary signal-class restrictions.

4. Acceptable G-PID list: a list of G-PIDs corresponding to the
    "client" digital streams that is compatible with this device

Note that the bitrate of the signal does not change over the LSP.
This can be communicated as an LSP parameter; therefore, this
information would be available for any NE that needs to use it for
configuration. Hence, it is not necessary to have "configuration
type" for the NE with respect to bitrate.

Output constraints:

1. Output modulation: (a) same as input, (b) list of available types

2. FEC options: (a) same as input, (b) list of available codes

Processing capabilities:

1. Regeneration: (a) 1R, (b) 2R, (c) 3R, (d) list of selectable
    regeneration types

2. Fault and performance monitoring: (a) G-PID particular
    capabilities, (b) optical performance monitoring capabilities.

Note that such parameters could be specified on (a) a network-
element-wide basis, (b) a per-port basis, or (c) a per-regenerator
basis. Typically, such information has been on a per-port basis; see
the GMPLS interface switching capability descriptor [RFC4202].

6.2.2. Wavelength-Specific Availability Information

For wavelength assignment, it is necessary to know which specific
wavelengths are available and which are occupied if a combined RWA
process or separate WA process is run as discussed in Sections 4.1.1
and 4.1.2. This is currently not possible with GMPLS routing.

In the routing extensions for GMPLS [RFC4202], requirements for
layer-specific TE attributes are discussed. RWA 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 DWDM systems range from 16
channels to 128 channels, with advanced laboratory systems with as
many as 300 channels. Given these channel limitations, if the

approach of a global wavelength to label mapping or furnishing the local mappings to the PCEs is taken, representing the use of wavelengths via a simple bitmap is feasible [Gen-Encode].

6.2.3. WSON Routing Information Summary

The following table summarizes the WSON information that could be conveyed via GMPLS routing and attempts to classify that information according to its static or dynamic nature and its association 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
Optical transmitter range	Static	Link(2)
Wavelength conversion capabilities	Static(3)	Node
Maximum bandwidth per wavelength	Static	Link
Wavelength availability	Dynamic(4)	Link
Signal compatibility and processing	Static/Dynamic	Node

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 that it may be desirable to include regeneration capabilities here since OEO converters are also regenerators.

4. This is 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 + Distributed WA via Signaling, only the following information is needed:

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

Information models and compact encodings for this information are
provided in [WSON-Info], [Gen-Encode], and [WSON-Encode].

6.3. Optical Path Computation and Implications for PCE

As previously noted, RWA can be computationally intensive. Such
computationally intensive path computations and optimizations were
part of the impetus for the PCE architecture [RFC4655].

The Path Computation Element Communication Protocol (PCEP) defines
the procedures necessary to support both sequential [RFC5440] and
Global Concurrent Optimization (GCO) path computations [RFC5557].
With some protocol enhancement, the PCEP is well positioned to
support WSON-enabled RWA computation.

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

6.3.1. Optical Path Constraints and Characteristics

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

o Batch optimization, multiple optical paths requested at one time
   (PCE-GCO)

o Optical path(s) and backup optical path(s) requested at one time
   (PCEP)

o Single optical path requested at a time (PCEP)

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

Optical path constraints include:

o Bidirectional assignment of wavelengths

o Possible simultaneous assignment of wavelength to primary and
   backup paths

o Tuning range constraint on optical transmitter

6.3.2. Electro-Optical Element Signal Compatibility

When requesting a path computation to PCE, the PCC should be able to
indicate the following:

o The G-PID type of an LSP

o The signal attributes at the transmitter (at the source): (i)
   modulation type, (ii) FEC type

o The signal attributes at the receiver (at the sink): (i)
   modulation type, (ii) FEC type

The PCE should be able to respond to the PCC with the following:

o The conformity of the requested optical characteristics associated
   with the resulting LSP with the source, sink, and NE along the LSP

o Additional LSP attributes modified along the path (e.g.,
   modulation format change)

6.3.3. Discovery of RWA-Capable PCEs

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

Recent progress on objective functions in PCE [RFC5541] would allow
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
the most evenly distributed link utilization.

This implies that PCEP would easily accommodate a 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.

7. Security Considerations

This document does not require changes 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 may make 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 RWA represents a disclosure of network capabilities that an operator may wish to keep private. Consideration should be given to securing this information. For a general discussion on MPLS- and GMPLS-related security issues, see the MPLS/GMPLS security framework [RFC5920].

8. Acknowledgments

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