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Framework for GMPLS and PCE Control of Spectrum Switched Optical Networks

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Abstract

A new flexible grid of DWDM has been developed within the ITU-T Study Group 15 to allow a more efficient spectrum allocation. In such environment a data plane connection is switched based on the allocated variable width optical spectrum frequency slot. This new switching capability is referred to as Spectrum Switched Optical Networks (SSON). This draft describes the framework for the application of a GMPLS control plane to a SSON.

Conventions used in this document

The key words "MUST", "MUST NOT", "REQUIRED", "SHALL", "SHALL NOT", "SHOULD", "SHOULD NOT", "RECOMMENDED", "MAY", and "OPTIONAL" in this document are to be interpreted as described in RFC-2119 [RFC2119].

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1. Introduction

[G.694.1v1] defines the DWDM frequency grids for WDM applications. A frequency grid is a reference set of frequencies used to denote allowed nominal central frequencies that may be used for defining applications. The channel spacing, i.e. the frequency spacing between two allowed nominal central frequencies could be 12.5 GHz, 25 GHz, 50 GHz, 100 GHz or integer multiples of 100 GHz as defined in [G.694.1v1]. The frequency spacing of the channels on a fiber is fixed.

The data rate of optical signals becomes higher and higher with the advancement of the optical technology. In the near future, it is anticipated that high data rate signals (beyond 100 Gbit/s or even 400 Gbit/s) will be deployed in optical networks. These signals may not be accommodated in the channel spacing specified in old [G.694.1v1]. Moreover, ''mixed rate'' scenarios will be prevalent, and the optical signals with different rates may require different spectrum width. As a result, when the optical signals with different rates are mixed to be transmitted on the same fiber, the frequency allocation needs to be more flexible so as to improve spectral efficiency.

An updated version of [G.694.1v1], i.e., [G.FLEXIGRID] has been consented in December 2011 in support of flexible grids. The terms ''frequency slot (the frequency range allocated to a channel and unavailable to other channels within a flexible grid)'' and ''slot width'' (the full width of a frequency slot in a flexible grid) are introduced to address flexible grid extensions. A channel is represented as a LSC (Lambda Switching Capable) LSP in the control plane, and it means that a LSC LSP should occupy a frequency slot on each fiber it traverses. In the case of flexible grid, different LSC LSPs may have different slot widths on a fiber.

Thus the concept of Wavelength Switched Optical Network(WSON) is extended to Spectrum Switched Optical Network (SSON) which includes flexible capabilities (i.e. flexi-grid). In SSON, a data plane connection is switched based on an optical spectrum frequency slot of a variable (flexible) slot width, rather than based on a single wavelength within a fixed grid and with a fixed channel spacing as is the case for WSON. In this sense, a WSON can be seen as a particular case of a SSON in which all slot widths are equal and central frequencies depend on the used channel spacing.

WSON related documents are currently being developed with the focus of the GMPLS control of fixed grid optical networks. This document describes the new characteristics of SSON and provides the framework of GMPLS control for the new features of SSON beyond WSON.

Note that this document focuses on the general properties of SSON. Information related to optical impairments is out of its scope and will be addressed in a separate draft.

2. Terminology

Flexible Grid: a new WDM frequency grid defined with the aim of allowing flexible optical spectrum management, in which the Slot Width of the frequency ranges allocated to different channels are flexible (variable size).

Frequency Range: a frequency range is defined as the portion of frequency spectrum included between a lowest and a highest frequency.

Frequency Slot: the frequency range allocated to a slot and unavailable to other slots within a flexible grid. A frequency slot is defined by its nominal central frequency and its slot width.

Slot Width: the full width (in Hz) of a frequency slot. A slot width can be expressed as a multiple (m) of a basic slot width (e.g. 12.5 GHz).

SSON: Spectrum-Switched Optical Network. An optical network in which a data plane connection is switched based on an optical spectrum frequency slot of a variable slot width, rather than based on a fixed grid and fixed slot width. Please note that a Wavelength Switched Optical Network (WSON) can be seen as a particular case of SSON in which all slot widths are equal and depend on the used channel spacing.

Flexi-LSP: a control plane construct that represents a data plane connection in which the switching involves a frequency slot of a variable (flexible) slot width. The mapped client signal is transported over the frequency slot, using spectrum efficient modulations such as Coherent Optical Orthogonal Frequency Division Multiplexing (CO-OFDM) and Forward Error Correction (FEC) techniques. Although still in the scope of LSC, the term flexi-LSP is used, when needed, to differentiate from regular WSON LSP in which switching is based on a nominal wavelength.

RSA: Routing and Spectrum Assignment. As opposed to the typical Routing and Wavelength Assignment (RWA) problem of traditional WDM

networks, the flexibility in SSON leads to spectral contiguous constraint, which means that when assigning the spectral resources to single connections, the resources assigned to them must be contiguous over the entire connections in the spectrum domain. RSA is introduced to describe the routing and spectrum assignment procedures.

3. New characteristics of SSON

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. WSON framework is described in [RFC6163]. The introduced flexible grid brings some changes on GMPLS controlled optical networks.

The concept of WSON is extended to SSON, to highlight that such subsystems are extended with flexible capabilities (i.e. flexi-grid). Note that, when modeling SSONs, a WSON can be seen as a particular case of SSON where all LSC LSPs use a fixed (and equal) slot width which depends on the used channel spacing.

In WSON, the joint determination of an optical path (physical route) along with the nominal wavelength on a fiber is known as Routing and Wavelength Assignment (RWA). Wavelength Assignment (WA) is the determination of which wavelength can be used for a specific optical path. In analogy with WSON, in SSON, the determination of a path and a frequency slot (including both central frequency and slot width) is referred to as Routing and Spectrum Assignment (RSA). Spectrum Assignment (SA) is the process of determining the spectrum range that can be used for one specific flex-LSP given a physical route.

Compared to WSON, flexibility needs to be introduced in optical network devices such as ROADMs or optical transponders in order to fully benefit from SSON (flexible grid) improved spectrum management. Consequently, transceivers may be able to fully leverage flexible optical channels with advanced modulation formats, and ROADMs may need to be extended to allow flexible spectrum switching.

A flexible grid is defined for the DWDM system in [G.FLEXIGRID]. Compared to fixed grids a flexible grid has a smaller granularity for the central frequencies and the slot width may range from say, 12.5 GHz to hundreds of GHz, in order to accommodate different client data rates. The subsequent sections analyze the new characteristics of flexible grid based on standard [G.FLEXIGRID],

and then model ROADMs, and optical transponders in SSON with an emphasis on those aspects that are of relevance to the control plane.

3.1. Overview of Flexible Grid

o Central Frequency

According to the definition of flexible DWDM grid in [G.FLEXIGRID], the allowed nominal central frequencies are calculated as in the case of flexible grid:

```
          Central Frequency = 193.1 THz + n * 0.00625 THz
```

Where 193.1 THz is ITU-T ''anchor frequency'' for transmission over the C band, n is a positive or negative integer including 0 and 0.00625 THz is the nominal central frequency granularity.

o Slot Width

A slot width is defined by:

```
                           12.5 GHz * m
```

Where m is a positive integer and 12.5 GHz is the slot width granularity.

Note that, when flexi-grid is supported on a WDM link, the slot width of different flexi-LSPs may be different.

The WDM link for flexible grid can be represented as shown in figure 1.

```
  -9 -8 -7 -6 -5 -4 -3 -2 -1  0  1  2  3  4  5  6  7  8  9 10 11
...+--+--+--+--+--+--+--+--+--+--+--+--+--+--+--+--+--+--+--+--+--...

                              ^
                           193.1THz
```

Figure 1 Fiber link model for flexible grid

The symbol'+' represents the allowed nominal central frequencies. The symbol ''--" represents the basic 6.25 GHz frequency slot. The number on the top of the line represents the 'n' in the frequency calculation formula. The nominal central frequency is 193.1 THz when n equals zero.

As Described in [G.FLEXIGRID], the flexible DWDM grid has a nominal central frequency granularity of 6.25 GHz and a slot width granularity of 12.5 GHz. However, devices or applications that make use of the flexible grid, may not have to be capable of supporting every possible slot width or central frequency granularity. For example, ROADM and transceivers in SSON may support subset of all possible slot width or posit defined in [G.FLEXIGRID].

3.2. ROADM

To support flexi grid, a ROADM is a key device which allows spectrum-based optical switching. A classic 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)
                    |                       |
                    +-----------------------+
                    | O    | O    | O    | O
                    | |    | |    | |    | |
                    O |    O |    O |    O |
 Tributary Side:   E5 I5  E6 I6  E7 I7  E8 I8
```

Figure 2 Degree-4 Bidirectional ROADM

The key feature of ROADMs is their highly asymmetric switching capability which is described in [RFC6163] in detail. The asymmetric switching feature of flexible ROADM in SSON is similar to fixed ROADM in WSON. The ports on ROADM include line side port which is connected to WDM link, tributary side input/output port which is connected to transmitter/receiver. The main difference between ROADMs in SSON and WSON is the capability of ports on ROADM, which are characterized as follows:

From a SSON control plane perspective (in terms of path computation and resource allocation), ROADMs line side ports are characterized by the following aspects:

- o Available frequency ranges: the set or union of frequency ranges that are not allocated (i.e. available or unused. The relative grouping and distribution of available frequency ranges in a fiber is usually referred to as ''fragmentation''.

- o Available slot width ranges: the set or union of slot width ranges supported by ROADM. It includes the following information:

  - o Slot width threshold: the minimum and maximum Slot Width supported by ROADM. For example, the slot width can be from 50GHz to 200GHz.

  - o Step granularity: the minimum step by which the optical filter bandwidth of ROADM can be increased or decreased. This parameter is typically equal to slot width granularity defined in [G.FLEXIGRID] (i.e. 12.5GHz) or integer multiples of 12.5GHz.

These properties can be injected into the link parameters from the control plane perspective, which is described in Section 5.

Since the tributary side port is connected to a transmitter and receiver, the characterization of tributary side ports is described in the next section.

3.3. Optical Transmitters and Receivers

In WSON, the optical transmitter is the wavelength source and the optical receiver is the wavelength sink of the WDM system. In each direction, the wavelength used by the transmitter and receiver along a path shall be consistent if no wavelength converter is available. The central frequency used by a transmitter or receiver may be fixed or tunable.

In SSON the optical spectrum (frequency slot width) used by different flexi-LSPs may be variable. Optical transmitters/receivers may have different restriction on the following properties:

- o Available central frequencies: The set of central frequencies which can be used by an optical transmitter/receiver.

- o Slot width: The slot width needed by a transmitter/receiver.

  The slot width is dependent on bit rate and modulation format. For one specific transmitter, the bit rate and modulation format may be tunable, so slot width would be determined by the modulation format used at a given bit rate.

Similarly, other information on transmitters and receivers capabilities, in regard to signal processing is needed to perform efficient RSA, much like in WSON [WSON-ENCODE].

4. Routing and Spectrum Assignment

A LSC flexi-LSP occupies a frequency slot, i.e. a range of frequencies, on each link the LSP traverses.

Much like in WSON, in which if there is no (available) wavelength converter in an optical network an LSP is subject to the ''wavelength continuity constraint'' (see section 4 of [RFC6163]), in SSON if the capability of shifting or converting the whole optical spectrum allocated to a flex-LSP is not available, the flexi-LSP is subject to the Optical ''Spectrum Continuity Constraint''.

Because of the limited availability of wavelength/spectrum converters (sparse translucent optical network) the wavelength/spectrum continuity constraint should always be considered. When available, information regarding spectrum conversion capabilities at the optical nodes may be used by RSA mechanisms.

The RSA process determines a route and frequency slot for a flexi-LSP. Note that the mapping between client signals data rates (10, 40, 100... Gbps) and optical slot widths (which are dependent on modulation formats and other physical layer parameters) is out of the scope of this document. The frequency slot can be deduced from the central frequency and slot width parameters as follows:

Lowest frequency = (central frequency) - (slot width)/2;

Highest frequency = (central frequency) + (slot width)/2.

Hence, when a route is computed the spectrum assignment process (SA) should determine the central frequency for a flexi-LSP based on the slot width and available central frequencies information of the transmitter and receiver, and the available frequency ranges information and available slot width ranges of the links that the route traverses.

Figure 2 shows two LSC LSPs that traverse a link.

```
                        Frequency Slot 1     Frequency Slot 2
                        -------------     -------------------
                        |           |     |                 |
         -9 -8 -7 -6 -5 -4 -3 -2 -1  0  1  2  3  4  5  6  7  8  9 10 11
      ...+--+--+--+--+--+--+--+--+--+--+--+--+--+--+--+--+--+--+--+--+--...
                        -------------     -------------------
                              ^                     ^
                  Central F = 193.1THz    Central F = 193.14375 THz
                  Slot width = 25 GHz     Slot width = 37.5 GHz
```

Figure 2 Two LSC LSPs traverse a Link

The two wavelengths shown in figure 2 have the following meaning:

Flexi-LSP 1: central frequency = 193.1 THz, slot width = 25 GHz. It means the frequency slot [193.0875 THz, 193.1125 THz] is assigned to this LSC LSP.

Flexi-LSP 2: central frequency = 193.14375 THz, slot width = 37.5 GHz. It means the frequency slot [193.125 THz, 193.1625 THz] is assigned to this LSC LSP.

Note that the frequency slots of two LSC flexi-LSPs on a fiber do not overlap with each other, and a guard band may be considered to counteract inter-channel detrimental effects.

4.1. Architectural Approaches to RSA

Similar to RWA for fixed grids, different ways of performing RSA in conjunction with the control plane can be considered. The approaches included in this document are provided for reference purposes only; other possible options could also be deployed.

4.1.1. Combined RSA (R&SA)

In this case, a computation entity performs both routing and frequency slot assignment. The computation entity should have the detailed network information, e.g. connectivity topology constructed by nodes/links information, available frequency ranges on each link, node capability, etc.

The computation entity could reside on the following elements, which depends on the implementation:

o PCE: PCE gets the detailed network information and implements the RSA algorithm for RSA requests from the PCCs.

o Ingress node: Ingress node gets the detailed network information (e.g. through routing protocol) and implements the RSA algorithm when a LSC LSP request is received.

4.1.2. Separated RSA (R+SA)

In this case, routing computation and frequency slot assignment are performed by different entities. The first entity computes the routes and provides them to the second entity; the second entity assigns the frequency slot.

The first entity should get the connectivity topology to compute the proper routes; the second entity should get the available frequency ranges of the links and nodes' capabilities information to assign the spectrum.

4.1.3. Routing and Distributed SA (R+DSA)

In this case, one entity computes the route but the frequency slot assignment is performed hop-by-hop in a distributed way along the route. The available central frequencies which meet the wavelength continuity constraint should be collected hop by hop along the route. This procedure can be implemented by the GMPLS signaling protocol.

The GMPLS signaling procedure is similar to the one described in section 4.1.3 of [RFC6163] except that the label set should specify the available central frequencies that meet the slot width requirement of the LSC LSP, i.e. the frequency slot which is determined by the central frequency and slot width MUST NOT overlap with the existing LSC LSPs.

5. Requirements for GMPLS Control Plane

According to the different architecture approaches to RSA some additional requirements have to be considered for the GMPLS control of SSONs.

5.1. Routing

In the case of combined RSA architecture, the computation entity needs to get the detailed network information, i.e. connectivity topology, node capabilities and available frequency ranges of the links. Route computation is performed based on the connectivity topology and node capabilities; spectrum assignment is performed based on the available frequency ranges of the links. The computation entity may get the detailed network information by the GMPLS routing protocol.

Compared with [RFC6163], except wavelength-specific availability information, the connectivity topology and node capabilities are the same as WSON, which can be advertised by GMPLS routing protocol (refer to section 6.2 of [RFC6163]. This section analyses the necessary changes on link information brought by flexible grids.

5.1.1. Available Frequency Ranges of DWDM Links

In the case of flexible grids, channel central frequencies span from 193.1 THz towards both ends of the C band spectrum with 6.25 GHz granularity. Different LSC LSPs could make use of different slot widths on the same link. Hence, the available frequency ranges should be advertised.

5.1.2. Available Slot Width Ranges of DWDM Links

The available slot width ranges needs to be advertised in order to understand whether a LSC LSCP with a given slot width can be set up or not.

Whether a LSC LSP with a certain slot width can be set up or not is constrained by the available slot width ranges of flexible ROADM. So the available slot width ranges should be advertised.

5.1.3. Tunable Optical Transmitters and Receivers

The slot width of a LSC LSP is determined by the transmitter and receiver that could be mapped to ADD/DROP interfaces in WSON. Moreover their central frequency could be fixed or tunable, hence, both the slot width of an ADD/DROP interface and the available central frequencies should be advertised.

5.2. Signaling

Compared with [RFC6163], except identifying the resource (i.e., fixed wavelength for WSON and frequency resource for flexible grids), the other signaling requirements (e.g., unidirectional or bidirectional, with or without converters) are the same as WSON described in the section 6.1 of [RFC6163].

In the case of routing and distributed SA, GMPLS signaling can be used to allocate the frequency slot to a LSC LSP. This brings the following changes to the GMPLS signaling.

5.2.1. Slot Width Requirement

In order to allocate a proper frequency slot for a LSC LSP, the signaling should specify the slot width requirement of a LSC LSP. Then the intermediate nodes can collect the acceptable central frequencies that meet the slot width requirement hop by hop.

The tail-end node also needs to know the slot width of a LSC LSP to assign the proper frequency resource. Hence, the slot width requirement should be specified in the signaling message when a LSC LSP is being set up.

5.2.2. Frequency Slot Representation

The frequency slot can be determined by the central frequency (n value) and slot width (m value) as described in section 5. Such parameters should be able to be specified by the signaling protocol.

5.3. PCE

[WSON-PCE] describes the architecture and requirements of PCE for WSON. In the case of flexible grid, RSA instead of RWA is used for routing and frequency slot assignment. Hence PCE should implement RSA for flexible grids. The architecture and requirements of PCE for flexible grids are similar to what is described in [WSON-PCE]. This section describes the changes brought by flexible grids.

5.3.1. RSA Computation Type

A PCEP request within a PCReq message MUST be able to specify the computation type of the request:

o Combined RSA: Both the route and frequency slot should be provided by PCE.

o Routing Only: Only the route is requested to be provided by PCE.

The PCEP response within a PCRep Message MUST be able to specify the route and the frequency slot assigned to the route.

RSA in SSON MAY include the check of signal processing capabilities, which MAY be provided by the IGP. A PCC should be able to indicate additional restrictions for such signal compatibility, either on the endpoint or any given link (such as regeneration points).

A PCC MUST be able to specify whether the PCE MUST also assign a Modulation list and/or a FEC list, as defined in [WSON-ENCODE] and [WSON-PCE].

A PCC MUST be able to specify whether the PCE MUST or SHOULD include or exclude specific modulation formats and FEC mechanisms.

In the case where a valid path is not found, the response MUST be able to specify the reason (e.g., no route, spectrum not found, etc.)

5.3.2. RSA path re-optimization request/reply

For a re-optimization request, the PCEP request MUST provide the path to be re-optimized and include the following options:

o Re-optimize the path keeping the same frequency slot.

o Re-optimize spectrum keeping the same path.

o Re-optimize allowing both frequency slot and the path to change.

The corresponding PCEP response for the re-optimized request MUST provide the Re-optimized path and frequency slot.

In case a path is not found, the response MUST include the reason (e.g., no route, frequency slot not found, both of route and frequency slot not found, etc.)

5.3.3. Frequency Constraints

A PCE should consider the following constraints brought by the transmitters and receivers:

o Available central frequencies: The set of central frequencies that can be used by an optical transmitter or receiver.

o Slot width: The slot width needed by a transmitter or receiver.

These constraints may be provided by the requester (PCC) in the PCEP request or reside within the PCE's TEDB which stores the transponder's capabilities.

A PCC may also specify the frequency constraints for policy reasons. In this case, the constraints should be specified in the request sent to the PCE. In any case, the PCE will compute the route and assign the frequency slot to meet the constraints specified in

theafore mentioned request and it will then return the result of the path computation to the PCC in the corresponding response.

6. Security Considerations

This document does not introduce any further security issues other than those described in [RFC6163] and [RFC5920].

7. References

7.1. Normative References

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