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Framework for GMPLS based control of Flexi-grid DWDM networks
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Abstract

This document defines a framework and the associated control plane requirements for the GMPLS based control of flexi-grid DWDM networks. To allow efficient allocation of optical spectral bandwidth for high bit-rate systems, the International Telecommunication Union Telecommunication Standardization Sector (ITU-T) is extending the recommendations [G.694.1] and [G.872] to include the concept of flexible grid: a new DWDM grid has been developed within the ITU-T Study Group 15, by defining a set of nominal central frequencies, smaller channel spacings and the concept of "frequency slot". In such environment, a data plane connection is switched based on allocated, variable-sized frequency ranges within the ptical spectrum.

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1. Requirements Language

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 [RFC2119].

2. Introduction

The term "Flexible grid" (flexi-grid for short) as defined by the International Telecommunication Union Telecommunication Standardization Sector (ITU-T) study group 15 in the latest version of [G.694.1], refers to the updated set of nominal central frequencies (a frequency grid), channel spacings and optical spectrum management/allocation considerations that have been defined in order to allow an efficient and flexible allocation and configuration of optical spectral bandwidth for high bit-rate systems.

A key concept of flexi-grid is the "frequency slot"; a variable-sized optical frequency range that can be allocated to a data connection. As detailed later in the document, a frequency slot is characterized by its nominal central frequency and its slot width which, as per [G.694.1], is constrained to be a multiple of a given slot width granularity.

Compared to a traditional fixed grid network, which uses fixed size optical spectrum frequency ranges or "frequency slots" with typical channel separations of 50 GHz, a flexible grid network can select its media channels with a more flexible choice of slot widths, allocating as much optical spectrum as required, and allowing higher bit rates (e.g., 400G, 1T or higher).

From a networking perspective, a flexible grid network is assumed to be a layered network [G.872][G.800] in which the flexi-grid layer (also referred to as the media layer) is the server layer and the OCh Layer (also referred to as the signal layer) is the client layer. In the media layer, switching is based on a frequency slot, and the size of a media channel is given by the properties of the associated frequency slot. In this layered network, the media channel itself can be dimensioned to contain one or more Optical Channels.

As described in [RFC3945], GMPLS extends MPLS from supporting only Packet Switching Capable (PSC) interfaces and switching to also support four new classes of interfaces and switching that include Lambda Switch Capable (LSC).

A Wavelength Switched Optical Network (WSON), addressed in [RFC6163], is a term commonly used to refer to the application/deployment of a

Generalized Multi-Protocol Label Switching (GMPLS)-based control plane for the control (provisioning/recovery, etc) of a fixed grid WDM network. [editors' note: we need to think of the relationship of WSON and OCh switching. Are they equivalent? WSON includes regeneration, OCh does not? decoupling of lambda/OCh/OCC]

This document defines the framework for a GMPLS-based control of flexi-grid enabled DWDM networks (in the scope defined by ITU-T layered Optical Transport Networks [G.872], as well as a set of associated control plane requirements. An important design consideration relates to the decoupling of the management of the optical spectrum resource and the client signals to be transported. [Editor's note: a point was raised during the meeting that WSON has not made the separation between Och and Lambda (spectrum and signal are bundled)].

[Editors' note: this document will track changes and evolutions of [G.694.1] [G.872] documents until their final publication. This document is not expected to become RFC until then.]

[Editor's note: -00 as agreed during IETF83, the consideration of the concepts of Super-channel (a collection of one or more frequency slots to be treated as unified entity for management and control plane) and consequently Contiguous Spectrum Super-channel (a super-channel with a single frequency slot) and Split-Spectrum super-channel (a super-channel with multiple frequency slots) is postponed until the ITU-T data plane includes such physical layer entities, e.g., an ITU-T contribution exists. ITU-T is still discussing B100G Architecture]

[Editors' note: -01 this version reflects the agreements made during IETF84, notably concerning the focus in the media layer, terminology updates post ITU-T September meeting in Geneva and the deprecation of the ROADM term, in favor of the more concrete media layer switching element (media channel matrix).]

[Editors' note: -01 in partial answer to Gert question on the layered model, [G.872] footnote explains that this separation is necessary to allow the description of media elements that may act on more than a single OCh-P signal. See appendix IV within.]

3. Acronyms

FS: Frequency Slot

NCF: Nominal Central Frequency

OCh: Optical Channel

OCh-P: Optical Channel Payload

OCh-O: Optical Channel Overhead

OCC: Optical Channel Carrier

SWG: Slot Width Granularity

4. Terminology

The following is a list of terms (see [G.694.1] and [G.872]) reproduced here for completeness. [Editors' note: regarding wavebands, we agreed NOT to use the term in flexigrid. The term has been used inconsistently in fixed-grid networks and overlaps with the definition of frequency slot. If need be, a question will be sent to ITU-T asking for clarification regarding wavebands.]

Where appropriate, this documents also uses terminolgy and lexicography from [RFC4397].

[Editors' note: *important* these terms are not yet final and they may change / be replaced or obsoleted at any time.]

4.1. Frequency Slots

- o Nominal Central Frequency Granularity: 6.25 GHz (note: sometimes referred to as 0.00625 THz).

- o Nominal Central Frequency: each of the allowed frequencies as per the definition of flexible DWDM grid in [G.694.1]. The set of nominal central frequencies can be built using the following expression f = 193.1 THz + n x 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.

```
   -5 -4 -3 -2 -1  0  1  2  3  4  5     <- values of n
 ...+--+--+--+--+--+--+--+--+--+--+-
                   ^
                   193.1 THz <- anchor frequency
```

Figure 1: Anchor frequency and set of nominal central frequencies

o Slot Width Granularity: 12.5 GHz, as defined in [G.694.1].

o Slot Width: The slot width determines the "amount" of optical spectrum regardless of its actual "position" in the frequency axis. A slot width is constrained to be m x SWG (that is, m x 12.5 GHz), where m is an integer greater than or equal to 1.

o Frequency Slot: The frequency range allocated to a slot within the flexible grid and unavailable to other slots. A frequency slot is defined by its nominal central frequency and its slot width. Assuming a fixed and known central nominal frequency granularity, and assuming a fixed and known slot width granularity, a frequency slot is fully characterized by the values of 'n' and 'm'. Note that an equivalent characterization of a frequency slot is given by the start and end frequencies (i.e., a frequency range) which can, in turn, be defined by their respective values of 'n'.

```
      Frequency Slot 1     Frequency Slot 2
       -------------     -------------------
       |           |     |                 |
   -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: Example Frequency slots

The symbol '+' represents the allowed nominal central frequencies, the '--' represents the nominal central frequency granularity, and the '^' represents the slot nominal central frequency. The number on the top of the '+' symbol represents the 'n' in the frequency calculation formula. The nominal central frequency is 193.1 THz when n equals zero. Note that over a single frequency slot, one or multiple Optical Channels may be transported. Note that when there are multiple optical signals within frequency slot, then each signal still has its own central frequency. That is, the term "central frequency" applies to an Optical signal and the term "nominal central frequency" applies to a frequency slot. In other words, the Frequency Slot central frequency is independent of the signals central frequencies.

o Effective Frequency Slot: the effective frequency slot of a media channel is the common part of the frequency slots of the filter components along the media channel through a particular path

through the optical network. It is a logical construct derived from the (intersection of) frequency slots allocated to each device in the path. The effective frequency slot is an attribute of a media channel and, being a frequencly slot, it is described by its nominal central frequency and slot width. As an example, if there are two filters having slots with the same n but different m, then the common frequency slot has the smaller of the two m values. [Editor's note: within the GMPLS label swapping paradigm, the switched resource corresponds to the local frequency slot defined by the observable filters of the media layer switching element. The GMPLS label MUST identify the switched resource locally, and (as agreed during IETF84) is locally scoped to a link, even if the same frequency slot is allocated at all the hops of the path. Note that the requested slot width and the finally allocated slot witdh by a given node may be different, e.g., due to restrictions in the slot width granularity of the nodes. Due to the symmetric definition of frequency slot, allocations seem to be constrained to have the same nominal central frequency. It is important to note that if n changes along the path, it cannot be guaranteed that there is a valid common frequency slot. We must determine if different n's are allowed. We need to explain this rationale. e.g. what happens when the resulting slot cannot be characterized with n and m, see Figure 3 and Figure 4.].

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

       Frequency Slot 2
       -------------------
       |                 |
-3 -2 -1  0  1  2  3  4  5  6  7  8  9 10 11
..--+--+--+--+--X--+--+--+--+--+--+--+--+--+--...

===============================================
     Effective Frequency Slot
          -------------
          |           |
-3 -2 -1  0  1  2  3  4  5  6  7  8  9 10 11
..--+--+--+--+--X--+--+--+--+--+--+--+--+--+--...
```

Figure 3: Effective Frequency Slot

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

             Frequency Slot 2
             -------------------
             |                 |
      -3 -2 -1  0  1  2  3  4  5  6  7  8  9 10 11
      ..--+--+--+--+--X--+--+--+--+--+--+--+--+--+--+--...

   ===============================================
           Invalid Effective Frequency Slot - (n, m?)
             ----------
             |        |
      -3 -2 -1  0  1  2  3  4  5  6  7  8  9 10 11
      ..--+--+--+--+--+--+--+--+--+--+--+--+--+--+--+--...
```

Figure 4: Invalid Effective Frequency Slot

4.2. Media Layer, Elements and Channels

- Media Element: a media element only directs the optical signal or affects the properties of an optical signal, it does not modify the properties of the information that has been modulated to produce the optical signal. Examples of media elements include fibers, amplifiers, filters, switching matrices[Note: the data plane component of a LSR in the media layer is a media element, but not all media elements correspond to data plane nodes in the GMPLS network model.

- Media Channel: a media association that represents both the topology (i.e., path through the media) and the resource (frequency slot) that it occupies. As a topological construct, it represents a (effective) frequency slot supported by a concatenation of media elements (fibers, amplifiers, filters, switching matrices...). This term is used to identify the end-to-end physical layer entity with its corresponding (one or more) frequency slots local at each link filters.

- Network Media Channel: a media channel (media association) that supports a single OCh-P network connection. It represents the concatenation of all media elements between an OCh-P source and an OCh-P sink. [TODO: |Malcolm| explain the use case rationale to support a hierarchy of media channels, where a media channel acts as "pipe" for one or more network media channels and they are both

separate entities (IETF84). This may be tied to the concept of a "waveband" or express channel, as stated in [G.872] footnote 4.]

- OCh-P Frequency Slot: The spectrum allocated to a single OCh signal supported on a Network Media Channel.

4.3. Media Layer Switching

[Editors' note: we are not discarding O/E/O. If defined in a ITU-T network reference model with trail/terminations, considering optical channels i.e. with well-defined interfaces, reference points, and architectures. The implications of O/E/O will be also addressed once we have another context that includes them. In OTN from an OCh point of view end to end means from transponder to transponder, so if there is a 3R from ingress to egress there are 2 OCh which can have different 'n' and 'm'].

- Media Channel Matrixes: the media channel matrix provides flexible connectivity for the media channels. That is, it represents a point of flexibility where relationships between the media ports at the edge of a media channel matrix may be created and broken. The relationship between these ports is called a matrix channel. (Network) Media Channels are switched in a Media Channel Matrix.

In summary, the concept of frequency slot is a logical abstraction that represents a frequency range while the media layer represents the underlying media support. Media Channels are media associations, characterized by their (effective) frequency slot, respectively; and media channels are switched in media channel matrixes. In Figure 5 , a Media Channel has been configured and dimensioned to support two OCh-P, each transported in its own OCh-P frequency slot.

```
                         Media Channel Frequency Slot
     +-------------------------------X------------------------------+
     |                                                              |
     |      OCh-P Frequency Slot             OCh-P Frequency Slot   |
     |  +------------X-----------+       +----------X-----------+   |
     |   |       OCh-P           |       |      OCh-P           |   |
     |   |           o           |       |          o           |   |
     |   |           |           |       |          |           |   |
    -4  -3  -2  -1   0   1   2   3   4   5   6   7  8   9  10  11  12
...  +---+---+---+---+---+---+---+---+---+---+---+--+---+---+---+---+---...

...      <- Network Media Channel->     <- Network Media Channel->

...  <------------------------ Media Channel ----------------------->

     X - Frequency Slot Central Frequency

     o - signal central frequency
```

Figure 5: Example of Media Channel / Network Media Channels and associated frequency slots

4.4. Control Plane Terms

The following terms are defined in the scope of a GMPLS control plane. [Editors' note: the following ones were *not* agreed during IETF83 but are put here to be discussed.]

- o SSON: Spectrum-Switched Optical Network. An optical network in which a LSP is switched based on an frequency slot of a variable slot width of a media channel, 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.

- o Flexi-LSP: a control plane construct that represents a data plane connection in which the switching involves a frequency slot with variable slot width. Different Flexi-LSPs may have different slot widths. The term Flexi-LSP is used when needed to differentiate from regular WSON LSP in which switching is based on a nominal wavelength.

- o 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.

5. GMPLS applicability

The GMPLS control of the media layer deals with the establishment of media channels, which are switched in media channel matrixes. GMPLS labels locally represent the media channel and its associated frequency slot.

[Editors'note: As agreed during IETF84, current focus is on the media layer. Preliminaty agreement on the "m" parameter should appear in the label *and* the traffic parameters.]

6. DWDM flexi-grid enabled network element models

Similar to fixed grid networks, a flexible grid network is also constructed from subsystems that include Wavelength Division Multiplexing (WDM) links, tunable transmitters and receivers, i.e, media elements including media layer switching elements (media matrices), as well as electro-optical network elements, all of them with flexible grid characteristics.

[Editors' Note: In the scope of this document, and despite is informal use, the term Reconfigurable Optical Add / Drop Multiplexer, (ROADM) is avoided, in favor on media matrix. This avoid ambiguity. A ROADM can be implemented in terms on media matrices. Informationally, this document may provide an appendix on possible implementations of flexi-ROADMs in terms of media layer switching elements or matrices. XF: Whether ROADM is used or not doesn't matter with GMPLS Control Plane. I suggest to delete this statement. We may check G.798. Likewise, modeling of filters is out of scope of the current document IETF84, and is also considered implementation specific.]

As stated in [G.694.1] the flexible DWDM grid defined in Clause 7 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 be capable of supporting every possible slot width or position. In other words, applications may be defined where only a subset of the possible slot widths and positions are required to be supported. For example, an application could be defined where the nominal central frequency granularity is 12.5 GHz (by only requiring values of n that are even) and that only requires slot widths as a multiple of 25 GHz (by only requiring values of m that are even).

6.1. Network element constraints

[TODO: section needs to be rewritten, remove redundancy].

Optical transmitters/receivers may have different tunability constraints, and media channel matrixes may have switching restrictions. Additionally, a key feature of their implementation is their highly asymmetric switching capability which is described in [RFC6163] in detail. Media matrices include line side ports which are connected to DWDM links and tributary side input/output ports which can be connected to transmitters/receivers.

A set of common constraints can be defined :

- 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.

- o The minimum and maximum slot width.

- o Granularity: the optical hardware may not be able to select parameters with the lowest granularityy (e.g. 6.25 GHz for nominal central frequencies or 12.5 GHz for slot width granularity).

- o Available frequency ranges: the set or union of frequency ranges that are not allocated (i.e. available). 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 media matrices. It includes the following information.

  * Slot width threshold: the minimum and maximum Slot Width supported by the media matrix. For example, the slot width can be from 50GHz to 200GHz.

  * Step granularity: the minimum step by which the optical filter bandwidth of the media matrix can be increased or decreased. This parameter is typically equal to slot width granularity (i.e. 12.5GHz) or integer multiples of 12.5GHz.

[Editor's note: different configurations such as C/CD/CDC will be

added later. This section should state specifics to media channel matrices, ROADM models need to be moved to an appendix].

7. Layered Network Model

[Editors' note: OTN hierarchy is not fully covered. It is important to understand, where the FSC sits in the OTN hierarchy. This is also important from control plane perspective as this layer becomes the connection end points of optical layer service]. OCh / flexi-grid layered model.

```
 OCh AP                     Trail (OCh)                        OCh AP
  O- - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - O
  |                                                                |
 --- OCh-P                                                   OCh-P ---
 \ / source                                                  sink  \ /
  +                                                                +
  | OCh-P                 OCh-P Network Connection           OCh-P |
  O TCP - - - - - - - - - - - - - - - - - - - - - - - - - - - -TCP O
  |                                                                |
  |Channel Port             Network Media Channel       Channel Port |
  O - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - -  O
  |                                                                |
+--------+                 +-----------+                +----------+
|  \ (1) |  OCh-P LC       |    (1)    |  OCh-P LC      |   (1)  / |
|   \----|-----------------|-----------|----------------|-------/  |
+--------+ Link Channel    +-----------+  Link Channel  +----------+
Media Channel              Media Channel                Media Channel
  Matrix                     Matrix                       Matrix

(1) - Matrix Channel
```

Figure 6: Layered Network Model G.805

[Editors' note: we are replicating the figure here for reference, until the ITU-T document is official.

8. Topology view in Control Plane

[Note: the frequency slot matrix connection may interconnect one or more frequency slot channels which in turn may carry one or more Och signals.]

```
+--------------+                            +--------------+
|    OCh-P     |            TE              |     OCh-P    |  Virtual TE
|              |           link             |              |    link
|    Matrix    |o- - - - - - - - - - - - - o|    Matrix    |o- - - - - -
+--------------+                            +--------------+
               |       +---------+          |
               |       |  Media  |          |
               |o------| Channel |---------o|
                       |         |
                       | Matrix  |
                       +---------+
```

Figure 7: MRN/MLN topology view with TE link / FA

A SSON (network) refers to the GMPLS control of flexi-grid enabled DWDM optical networks and it encompasses both the signal and media layers. The WSON also encompasses the signal and media layers but, since there is no formal separation between OCh and OCC (1:1) this layer separation is often not considered. A WSON is a particular case of SSON in the which all slot widths are equal and depend on the channel spacing. In other words, since there is only a 1:1 relationship between OCh : OCC there is no need to have separate controlled layers, as if both layers are collapsed into one.

WSON	SSON	
OCh	OCh	Signal Layer
Optical Channel Carrier	Frequency Slot	Media Layer
1:1 single layer network	N:1 MRN/MLN (* see note)	Relationship SL : ML

Figure 8: Table Comparison WSON/SSON

Note that there is only one media layer switch matrix (one implementation is FlexGrid ROADM) in SSON, while "signal layer LSP is mainly for the purpose of management and control of individual optical signal". Signal layer LSPs (OChs) with the same attributions (such as source and destination) could be grouped into one media-layer LSP (media channel), which has advantages in spectral efficiency (reduce guard band between adjacent OChs in one FSC) and

LSP management. However, assuming some network elements indeed perform signal layer switch in SSON, there must be enough guard band between adjacent OChs in one media channel, in order to compensate filter concatenation effect and other effects caused by signal layer switching elements. In such condition, the separation of signal layer from media layer cannot bring any benefit in spectral efficiency and in other aspects, but make the network switch and control more complex. If two OChs must switch to different ports, it is better to carry them by diferent FSCs and the media layer switch is enough in this scenario.

9. Control Plane Requirements

[Editor's note: The considered topology view is a layered network, in which the media layer corresponds to the server layer (flexigrid) and the signal layer corresponds to the client layer (Och). This data plane modeling considers the flexigrid and the OCh as separate layers, However, this has implications on the interop/interworking with WSON and OCh switching. We need to manage a MRN for OCh and stitching for WSON? In other words, a key part of the fwk is to define how can we have MRN/MLN hierarchical relationship with Och/FS and yet stitching 1:1 between WSON and SSON? In this line: how does OCh switching and WSON relate, actually?]

[Editor's note: formal requirements such as noted in the comments will be added in a later version of the document].

Hierarchy spectrum management decouples media and signal, but from the point of view of the control plane, such separation of concerns implies the management of a MRN/MLN network. So Control Plane needs to differentiate signal LSP and media LSP. It should also need to support Hierarchy-LSP [RFC4206] The central frequency of each hop should be same along end-to-end media or signal LSP because of Spectrum Continuity Constraint. Otherwise some nodes need to convert the central frequency along media or signal LSP.

9.1. Neighbor Discovery and Link Property Correlation

[Editors' note: text from draft-li-ccamp-grid-property-lmp-01]

Potential interworking problems between fixed-grid DWDM and flexible-grid DWDM nodes, may appear. Additionally, even two flexible-grid optical nodes may have different grid properties, leading to link property conflict.

Devices or applications that make use of the flexible-grid may not be able to support every possible slot width. In other words,

applications may be defined where different grid granularity can be supported. Taking node F as an example, an application could be defined where the nominal central frequency granularity is 12.5 GHz requiring slot widths being multiple of 25 GHz. Therefore the link between two optical nodes with different grid granularity must be configured to align with the larger of both granularities. Besides, different nodes may have different slot width tuning ranges.

In summary, in a DWDM Link between two nodes, at least the following properties should be negotiated:

Grid capability (channel spacing) - Between fixed-grid and flexible-grid nodes.

Grid granularity - Between two flexible-grid nodes.

Slot width tuning range - Between two flexible-grid nodes.

9.2. Path Computation / Routing and Spectrum Assignment (RSA)

Much like in WSON, in which if there is no (available) wavelength converters in an optical network, an LSP is subject to the ''wavelength continuity constraint'' (see section 4 of [RFC6163]), if the capability of shifting or converting an allocated frequency slot, the 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 LSP. Hence, when a route is computed the spectrum assignment process (SA) should determine the central frequency and slot width 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.

9.2.1. 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.

9.2.1.1. 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 capabilities, etc.

The computation entity could reside either on a PCE or the ingress node.

9.2.1.2. 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.

9.2.1.3. 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 spectrum continuity constraint should be collected hop by hop along the route. This procedure can be implemented by the GMPLS signaling protocol.

9.3. Routing / Topology dissemination

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.

9.3.1. Available Frequency Ranges/slots 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 LSPs could make use of different slot widths on the same link. Hence, the available frequency ranges should be advertised.

9.3.2. Available Slot Width Ranges of DWDM Links

The available slot width ranges needs to be advertised, in combination with the Available frequency ranges, in order to verify whether a LSP with a given slot width can be set up or not; this is is constrained by the available slot width ranges of the media matrix Depending on the availability of the slot width ranges, it is possible to allocate more spectrum than strictly needed by the LSP.

9.3.3. Tunable Optical Transmitters and Receivers

The slot width of a 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.

9.3.4. Hierarchical Spectrum Management

[Editors' note: the part on the hierarchy of the optical spectrum could be confusing, we can discuss it]. The total available spectrum on a fiber could be described as a resource that can be divided by a media device into a set of Frequency Slots. In terms of managing spectrum, it is necessary to be able to speak about different granularities of managed spectrum. For example, a part of the spectrum could be assigned to a third party to manage. This need to partition creates the impression that spectrum is a hierarchy in view of Management and Control Plane. The hierarchy is created within a management system, and it is an access right hierarchy only. It is a management hierarchy without any actual resource hierarchy within fiber. The end of fiber is a link end and presents a fiber port which represents all of spectrum available on the fiber. Each spectrum allocation appears as Link Channel Port (i.e., frequency slot port) within fiber.

9.3.5. Information Model

Fixed DM grids can also be described via suitable choices of slots in a flexible DWDM grid. However, devices or applications that make use of the flexible grid may not be capable of supporting every possible

slot width or central frequency position. Following is the definition of information model, not intended to limit any IGP encoding implementation. For example, information required for routing/path selection may be the set of available nominal central frequencies from which a frequency slot of the required width can be allocated. A convenient encoding for this information (may be as a frequency slot or sets of contiguous slices) is further study in IGP encoding document.

[Editor's note: to be discussed]

```
<Available Spectrum in Fiber for frequency slot> ::=
    <Available Frequency Range-List>
    <Available Central Frequency Granularity >
    <Available Slot Width Granularity>
    <Minimal Slot Width>
    <Maximal Slot Width>

<Available Frequency Range-List> ::=
    <Available Frequency Range >[< Available Frequency Range-List>]

<Available Frequency Range >::=
  <Start Spectrum Position><End Spectrum Position> |
  <Sets of contiguous slices>

<Available Central Frequency Granularity> ::= n x 6.25GHz,
  where n is positive integer, such as 6.25GHz, 12.5GHz, 25GHz, 50GHz
  or 100GHz

<Available Slot Width Granularity> ::= m x 12.5GHz,
  where m is positive integer

<Minimal Slot Width> ::= j x 12.5GHz,
  j is a positive integer

<Maximal Slot Width> ::= k x 12.5GHz,
    k is a positive integer (k >= j)
```

Figure 9: Routing Information model

9.4. Signaling requirements

Note on explicit label control

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 LSP.

For R+DSA, 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 nominal central frequencies that meet the slot width requirement of the LSP.

9.4.1. Slot Width Requirement

[Editors' note: the signaling requirements need to be discussed. This is just preliminary text].

In order to allocate a proper frequency slot for a LSP, the signaling should specify its slot width requirement. 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 LSP to assign the proper frequency resource. Hence, the slot width requirement should be specified in the signaling message when a LSP is being set up. [Note: other methods may not need to collect availability]

9.4.2. Frequency Slot Representation

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

9.4.3. Relationship with MRN/MLN

9.4.3.1. OCh Layer

9.4.3.2. Media (frequency slot) layer

10. Control Plane Procedures

FFS. Postpone procedures such as resizing existing LSP(s) without deletion, which refers to increase or decrease of slot width value 'm' without changing the value of 'n', etc. until requirements have been identified. At present no hitless resizing protocol has been defined for OCh. Hitless resizing is defined for an ODU entity only.

11. Backwards (fixed-grid) compatibility, and WSON interworking

- SSON as evolution of WSON, same LSC, different Swcap?

- Potential problems with having the same swcap but the label format changes w.r.t. wson

- A new SwCap may need to be defined, LSC swcap already defined ISCD which can not be modified

- Role of LSP encoding type?

- Notion of hierarchy? There is no notion of hierarchy between WSON and flexi-grid / SSON - only interop / interwork.

Arguments for LSC switching capability

[QW] A LSP for an optical signal which has a bandwidth of 50GHz passes through both a fixed grid network and a flexible grid network. We assume that no OEOs exist in the LSP, so both the fixed grid path and flexible grid path occupy 50GHz. From the perspective of data plane, there is no change of the signal and no multiplexing when the fixed grid path interconnects with flexible grid path. From this scenario we can conclude that both fixed grid network path and flexible grid network path belong to the same layer. No notion of hierarchy exists between them.

[QW] stitching LSP which is described in [RFC5150] can be applied in one layer. LSP hierarchy allows more than one LSP to be mapped to an H-LSP, but in case of S-LSP, at most one LSP may be associated with an S-LSP. This is similar to the scenario of interconnection between fixed grid LSP and flexible grid LSP. Similar to an H-LSP, an S-LSP could be managed and advertised, although it is not required, as a TE link, either in the same TE domain as it was provisioned or a different one. Path setup procedure of stitching LSP can be applied in the scenario of interconnection between fixed grid path and flexible grid path.

```
           e2e LSP
           ++++++++++++++++++++++++++++++++++++> (LSP1-2)

                     LSP segment (flexi-LSP)
                   ====================> (LSP-AB)
                       C --- E --- G
                      /|\    |   / |\
                     / | \   |  /  | \
           R1 ---- A \ |  \  | /   | / B --- R2
                      \|   \ |/    |/
                       D --- F --- H

      fixed grid --A-- flexi-grid    --B-- fixed grid
```

Figure 10: LSP Stitching [RFC5150] and relationship with fixed-flexi

12. Misc & Summary of open Issues [To be removed at later versions]

o Will reuse a lot of work / procedures / encodings defined in the context of WSON

o At data rates of GBps / TBps, encoding bandwidths with bytes per second unit and IEEE 32-bit floating may be problematic / non scalable.

o Bandwidth fields not relevant since there is not a 1-to-1 mapping between bps and Hz, since it depends on the modulation format, fec, either there is an agreement on assuming best / worst case modulations and spectral efficiency.

o Label I: "m" is inherent part of the label, part of the switching, allows encode the "lightpath" in a ERO using Explicit Label Control, Still maintains that feature a cross-connect is defined by the tuple (port-in, label-in, port-out, label-out), allows a kind-of "best effort LSP"

o Label II: "m" is not part of the label but of the TSPEC, neds to be in the TSPEC to decouple client signal traffic specification and management of the optical spectrum, having in both places is redundant and open to incoherences, extra error checking.

o Label III: both, It reflects both the concept of resource request allocation / reservation and the concept of being inherent part of the switching.

13. Security Considerations

TBD

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