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O. Gonzalez de Dios, Ed.
Telefonica I+D
R. Casellas, Ed.
CTTC
F. Zhang
Huawei
X. Fu
ZTE
D. Ceccarelli
Ericsson
I. Hussain
Infinera

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Framework and Requirements 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) has extended 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, 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 optical spectrum.

Status of This Memo

This Internet-Draft will expire on August 18, 2014.

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Table of Contents

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 spacing 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, allowing high bit rate signals (e.g., 400G, 1T or higher) that do not fit in the fixed grid.

From a networking perspective, a flexible grid network is assumed to be a layered network [G.872][G.800] in which the media layer is the server layer and the optical 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 transports an Optical Tributary Signal.

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 in which media (spectrum) and signal are jointly considered

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.

3. Acronyms

EFS: Effective Frequency Slot

FS: Frequency Slot

NCF: Nominal Central Frequency

OCh: Optical Channel

OCh-P: Optical Channel Payload

OTS: Optical Tributary Signal

OCC: Optical Channel Carrier

SWG: Slot Width Granularity

4. Flexi-grid Networks

4.1. Flexi-grid in the context of OTN

[G.872] describes from a network level the functional architecture of Optical Transport Networks (OTN). The OTN is decomposed into independent layer networks with client/layer relationships among them. A simplified view of the OTN layers is shown in Figure 1.

```
+----------------+
| Digital Layer  |
+----------------+
| Signal Layer   |
+----------------+
|  Media Layer   |
+----------------+
```

Figure 1: Generic OTN overview

In the OTN layering context, the media layer is the server layer of the optical signal layer. The optical signal is guided to its destination by the media layer by means of a network media channel. 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 scope, this document uses the term flexi-grid enabled DWDM network to refer to a network in which switching is based on frequency slots defined using the flexible grid, and covers mainly the Media Layer as well as the required adaptations from the Signal layer. The present document is thus focused on the control and management of the media layer.

4.2. Terminology

This section presents the definition of the terms used in flexi-grid networks. These terms are included in the ITU-T recommendations [G.694.1], [G.872]), [G.870], [G.8080] and [G.959.1-2013].

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

4.2.1. Frequency Slots

This subsection is focused on the frequency slot related terms.

o Frequency Slot [G.694.1]: 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.

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 2: Anchor frequency and set of nominal central frequencies

Nominal Central Frequency Granularity: It is the spacing between allowed nominal central frequencies and it is set to 6.25 GHz (note: sometimes referred to as 0.00625 THz).

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

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.

```
         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 3: Example Frequency slots

o 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.

Effective Frequency Slot: the effective frequency slot of a media channel is the common part of the frequency slots 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 frequency slot, it is described by its nominal central frequency and slot width, according to the already described rules.

```
                        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 4: Effective Frequency Slot

4.2.2. Media Channels

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: It is a media channel that transports an Optical Tributary Signal [Editor's note: this definition goes beyond current G.870 definition, which is still tightened to a particular case of OTS, the OCh-P]

4.2.3. Media Layer Elements

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 [G.870]. Examples of media elements include fibers, amplifiers, filters and switching matrices.

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.

4.2.4. Optical Tributary Signals

Optical Tributary Signal [G.959.1-2013]: The optical signal that is placed within a network media channel for transport across the optical network. This may consist of a single modulated optical carrier or a group of modulated optical carriers or subcarriers. One particular example of Optical Tributary Signal is an Optical Channel Payload (OCh-P) [G.872].

4.3. Flexi-grid layered network model

In the OTN layered network, the network media channel transports a single Optical Tributary Signal (see Figure 5)

```
  |                    Optical Tributary Signal                 |
  O - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - O
  |                                                             |
  | Channel Port         Network Media Channel        Channel Port |
  O - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - O
  |                                                             |
+--------+                 +-----------+                +--------+
|  \ (1) |                 |    (1)    |                | (1)  / |
|   \----|-----------------|-----------|-------------------|-----/  |
+--------+ Link Channel    +-----------+  Link Channel     +--------+
  Media Channel            Media Channel               Media Channel
  Matrix                   Matrix                      Matrix

(1) - Matrix Channel

             Figure 5: Simplified Layered Network Model
```

A particular example of Optical Tributary Signal is the OCh-P. Figure Figure 6 shows the example of the layered network model particularized for the OCH-P case, as defined in G.805.

```
    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 according to G.805

By definition a network media channel only supports a single Optical Tributary signal. How several Optical Tributary signals are bound together is out of the scope of the present document and is a matter of the signal layer.

4.3.1. Hierarchy in the Media Layer

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. From the control and management perspective, a media channel can be logically splited in other media channels.

In Figure 7 , a Media Channel has been configured and dimensioned to support two network media channels, each of them carrying one optical tributary signal.

```
                            Media Channel Frequency Slot
    +-------------------------------X------------------------------+
    |                                                              |
    |       Frequency Slot                  Frequency Slot         |
    |   +------------X-----------+      +----------X-----------+   |
    |   | Opt Tributary Signal  |       | Opt Tributary Signal |   |
    |   |           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 7: Example of Media Channel / Network Media Channels and associated frequency slots

4.3.2. 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.

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).

5. GMPLS applicability

The goal of this section is to provide an insight of the application of GMPLS to control flexi-grid networks, while specific requirements are covered in the next section. The present framework is aimed at controlling the media layer within the Optical Transport Network (OTN) hierarchy and the required adaptations of the signal layer. This document also defines the term SSON (Spectrum-Switched Optical Network) to refer to a Flexi-grid enabled DWDM network that is controlled by a GMPLS/PCE control plane.

This section provides a mapping of the ITU-T G.872 architectural aspects to GMPLS/Control plane terms, and considers the relationship between the architectural concept/construct of media channel and its control plane representations (e.g. as a TE link).

5.1. General considerations

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. Network media channels are considered a particular case of media channels when the end points are transceivers (that is, source and destination of an Optical Tributary Signal)

5.2. Considerations on TE Links

From a theoretical / abstract point of view, a fiber can be modeled has having a frequency slot that ranges from (-inf, +inf). This representation helps understand the relationship between frequency slots / ranges.

The frequency slot is a local concept that applies locally to a component / element. When applied to a media channel, we are referring to its effective frequency slot as defined in [G.872].

The association of a filter, a fiber and a filter is a media channel in its most basic form, which from the control plane perspective may modeled as a (physical) TE-link with a contiguous optical spectrum at start of day. A means to represent this is that the portion of spectrum available at time t0 depends on which filters are placed at the ends of the fiber and how they have been configured. Once filters are placed we have the one hop media channel. In practical terms, associating a fiber with the terminating filters determines the usable optical spectrum.

```
   -----------------+                             +-----------------+
                    |                             |
           +--------+                             +--------+
           |        |                             |        |  +---------
       ---o|        ===============================        o--|
           |        |             Fiber           |        |  | --\  /--
       ---o|        |                             |        o--|    \/
           |        |                             |        |  |    /\
       ---o|        ===============================        o--| --/  \--
           | Filter |                             | Filter |  |
           |        |                             |        |  +---------
           +--------+                             +--------+
                    |                             |
                 |------- Basic Media Channel  ---------|
   -----------------+                             +-----------------+


         --------+                                      +--------
                 |--------------------------------------|
          LSR    |              TE link                 |  LSR
                 |--------------------------------------|
        +--------+                                      +--------
```

Figure 8: (Basic) Media channel and TE link

Additionally, when a cross-connect for a specific frequency slot is considered, the underlying media support is still a media channel, augmented, so to speak, with a bigger association of media elements and a resulting effective slot. When this media channel is the result of the association of basic media channels and media layer matrix cross-connects, this architectural construct can be represented as / corresponds to a Label Switched Path (LSP) from a control plane perspective. In other words, It is possible to "concatenate" several media channels (e.g. Patch on intermediate nodes) to create a single media channel.

```
   -----------+       +------------------------------+       +----------
              |       |                              |       |
       +------+       +------+                +------+       +------+
       |      |       |      |  +----------+  |      |       |      |
    --o|      =========      o--|          |--o      =========      o--
       |      | Fiber |      |  | --\  /-- |  |      | Fiber |      |
    --o|      |       |      o--|    \/    |--o      |       |      o--
       |      |       |      |  |    /\    |  |      |       |      |
    --o|      =========      o--***********|--o      =========      o--
       |Filter|       |Filter|  |          |  |Filter|       |Filter|
       |      |       |      |                |      |       |      |
       +------+       +------+                +------+       +------+
              |       |                              |       |
          <- Basic Media ->    <- Matrix ->       <- Basic Media->
              |Channel|           Channel            |Channel|
   -----------+       +------------------------------+       +----------

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

     -----+                  +---------------+                  +-------
          |------------------|               |------------------|
     LSR  |       TE link    |       LSR     |   TE link        |   LSR
          |------------------|               |------------------|
     -----+                  +---------------+                  +-------
```

Figure 9: Extended Media Channel

Additionally, if appropriate, it can also be represented as a TE link or Forwarding Adjacency (FA), augmenting the control plane network model.

```
   -----------+       +------------------------------+       +----------
              |       |                              |       |
       +------+       +------+                +------+       +------+
       |      |       |      |  +----------+  |      |       |      |
    --o|      =========      o--|          |--o      =========      o--
       |      | Fiber |      |  | --\  /-- |  |      | Fiber |      |
    --o|      |       |      o--|    \/    |--o      |       |      o--
       |      |       |      |  |    /\    |  |      |       |      |
    --o|      =========      o--***********|--o      =========      o--
       |Filter|       |Filter|  |          |  |Filter|       |Filter|
       |      |       |      |                |      |       |      |
       +------+       +------+                +------+       +------+
              |       |                              |       |
   -----------+       +------------------------------+       +----------

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

    +-----+                                                      +------
          |------------------------------------------------------|
    LSR   |                               TE link                |  LSR
          |------------------------------------------------------|
    +-----+                                                      +------
```

Figure 10: Extended Media Channel / TE Link / FA

5.3. Considerations on Labeled Switched Path (LSP) in Flexi-grid

The flexi-grid LSP is seen as a control plane representation of a media channel. Since network media channels are media channels, an LSP may also be the control plane representation of a network media channel, in a particular context. From a control plane perspective, the main difference (regardless of the actual effective frequency slot which may be dimensioned arbitrarily) is that the LSP that represents a network media channel also includes the endpoints (transceivers) , including the cross-connects at the ingress / egress nodes. The ports towards the client can still be represented as interfaces from the control plane perspective.

Figure 11 describes an LSP routed along 3 nodes. The LSP is terminated before the optical matrix of the ingress and egress nodes and can represent a Media Channel. This case does NOT (and cannot) represent a network media channel as it does not include (and cannot include) the transceivers.

```
   ----------+       +--------------------------------+       +---------
             |       |                                |       |
          +------+       +------+                  +------+       +------+
```

```
   ----------+       +--------------------------------+       +---------
             |       |                                |       |
      +------+       +------+                  +------+       +------+
      |      |       |      |   +----------+   |      |       |      |
    -o|      =========      o---|          |---o      =========      o-
      |      | Fiber |      |   | --\  /-- |   |      | Fiber |      |
    -o|>>>>>>>>>>>>>>>>>>>>>>>>>>>>>>>>>>>>>>>>>>>>>>>>>>>>>>>>>>>>>>o-
      |      |       |      |   |    /\    |   |      |       |      |
    -o|      =========      o---***********|---o      =========      o-
      |Filter|       |Filter|   |          |   |Filter|       |Filter|
      |      |       |      |                  |      |       |      |
      +------+       +------+                  +------+       +------+
             |       |                                |       |
   ----------+       +--------------------------------+       +---------

           >>>>>>>>>>>>>>>>>>>>>>>>>>>> LSP >>>>>>>>>>>>>>>>>>>>>>>>
      -----+                  +---------------+                +-----
           |------------------|               |----------------|
      LSR  |       TE link    |     LSR       |      TE link   | LSR
           |------------------|               |----------------|
      -----+                  +---------------+                +-----
```

Figure 11: Flex-grid LSP representing a media channel that starts at the filter of the outgoing interface of the ingress LSR and ends at the filter of the incoming interface of the egress LSR

In Figure 12 a Network Media Channel is represented as terminated at the DWDM side of the transponder, this is commonly named as OCh-trail connection.

```
   |--------------------- Network Media Channel ----------------------|

        +----------------------+          +----------------------+
        |                                 |                      |
        +------+        +------+          +------+        +------+
        |      | +----+ |      |          |      | +----+ |      |OCh-P
   OCh-P|      o-|    |-o      |  +-----+  |      o-|    |-o      |sink
    src |      | |    | |      ===+-+ +-+==|      | |    | |      O---|R
   T|***o******o********************************************************
        |      | |\  /| |         | | | |  |      | |\  /| |      |
        |      o-| \/ |-o      ===| | | |==|      o-| \/ |-o      |
        |      | | /\ | |      |  +-+ +-+  |      | | /\ | |      |
        |      o-|/  \|-o      |  |  \/ |  |      o-|/  \|-o      |
        |Filter| |    | |Filter|  |  /\ |  |Filter| |    | |Filter|
        +------+ |    | +------+  +-----+  +------+ |    | +------+
        |        |    |        |          |        |    |        |
        +----------------------+          +----------------------+
                                      LSP
   <------------------------------------------------------------------->

                                      LSP
    <------------------------------------------------------------------>
         +-----+                   +--------+                +-----+
    o--- |     |-------------------|        |----------------|     |---o
         | LSR |       TE link     |  LSR   |   TE link      | LSR |
         |     |-------------------|        |----------------|     |
         +-----+                   +--------+                +-----+
```

Figure 12: LSP representing a network media channel (OCh-Trail)

In a third case, a Network Media Channel terminated on the Filter ports of the Ingress and Egress nodes. This is named in G.872 as OCh-NC (we need to discuss the implications, if any, once modeled at the control plane level of models B and C).

```
     |--------------------  Network Media Channel --------------------|

     +-------------------------+               +-------------------------+
     +------+       +------+                   +------+          +------+
     |      | +----+ |      |                  |      | +----+ |      |
     |      o-|    |-o      |    +------+      |      o-|    |-o      |
     |      | |    | |      =====+-+  +-+=====|      | |    | |      |
   T-o******o**********************************************************O-R
     |      | |\  /| |           | |  | |      |      | |\  /| |      |
     |      o-| \/ |-o      =====| |  | |=====|      o-| \/ |-o      |
     |      | | /\ | |      |    +-+  +-+      |      | | /\ | |      |
     |      o-|/  \|-o      |    |  \/  |      |      o-|/  \|-o      |
     |Filter| |    | |Filter|    |  /\  |      |Filter| |    | |Filter|
     +------+ |    | +------+    +------+      +------+ |    | +------+
     |        |    |        |                  |        |    |        |
     +----------------------+                  +----------------------+
     <------------------------------------------------------------------>
                                LSP

                                 LSP
     <-------------------------------------------------------------->
      +-----+                    +---------+                 +-----+
   o--|     |--------------------|         |-----------------|     |--o
      | LSR |       TE link      |   LSR   |     TE link     | LSR |
      |     |--------------------|         |-----------------|     |
      +-----+                    +---------+                 +-----+
```

Figure 13: LSP representing a network media channel (OCh-P NC)

[Note: not clear the difference, from a control plane perspective, of figs Figure 12 and Figure 13.]

Applying the notion of hierarchy at the media layer, by using the LSP as a FA, the media channel created can support multiple (sub) media channels. [Editot note : a specific behavior related to Hierarchies will be verified at a later point in time].

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

Figure 14: MRN/MLN topology view with TE link / FA

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.

5.4. Control Plane modeling of Network elements

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 The minimum and maximum slot width.

- o Granularity: the optical hardware may not be able to select parameters with the lowest granularity (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].

5.5. Media Layer Resource Allocation considerations

A media channel has an associated effective frequency slot. From the perspective of network control and management, this effective slot is seen as the "usable" frequency slot end to end. The establishment of an LSP related the establishment of the media channel and effective frequency slot.

In this context, when used unqualified, the frequency slot is a local term, which applies at each hop. An effective frequency slot applies at the media chall (LSP) level

A "service" request is characterized as a minimum, by its required effective slot width. This does not preclude that the request may add additional constraints such as imposing also the nominal central frequency. A given frequency slot is requested for the media channel say, with the Path message. Regardless of the actual encoding, the Path message sender descriptor sender_tspec shall specify a minimum frequency slot width that needs to be fulfilled.

In order to allocate a proper effective frequency slot for a LSP, the signaling should specify its required slot width.

An effective frequency slot must equally be described in terms of a central nominal frequency and its slot width (in terms of usable spectrum of the effective frequency slot). That is, one must be able to obtain an end-to-end equivalent n and m parameters. We refer to this as the "effective frequency slot of the media channel/LSP must be valid".

In GMPLS the requested effective frequency slot is represented to the TSpec and the effective frequency slot is mapped to the FlowSpec.

The switched element corresponds in GMPLS to the 'label'. As in flexi-grid the switched element is a frequency slot, the label represents a frequency slot. Consequently, the label in flexi-grid must convey the necessary information to obtain the frequency slot characteristics (i.e, center and width, the n and m parameters). The frequency slot is locally identified by the label

The local frequency slot may change at each hop, typically given hardware constraints (e.g. a given node cannot support the finest granularity). Locally n and m may change. As long as a given downstream node allocates enough optical spectrum, m can be different along the path. This covers the issue where concrete media matrices can have different slot width granularities. Such "local" m will appear in the allocated label that encodes the frequency slot as well as the flow descriptor flowspec.

Different modes are considered: RSA with explicit label control, and 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. 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. 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].

Regarding how a GMPLS control plane can assign n and m, different cases can apply:

a) n and m can both change. It is the effective slot what matters. Some entity needs to make sure the effective frequency slot remains valid.

b) m can change; n needs to be the same along the path. This ensures that the nominal central frequency stays the same.

c) n and m need to be the same.

d)n can change, m needs to be the same.

In consequence, an entity such as a PCE can make sure that the n and m stay the same along the path. Any constraint (including frequency slot and width granularities) is taken into account during path computation. alternatively, A PCE (or a source node) can compute a path and the actual frequency slot assignment is done, for example, with a distributed (signaling) procedure:

Each downstream node ensures that m is >= requested_m.

Since a downstream node cannot foresee what an upstream node will allocate in turn, a way we can ensure that the effective frequency slot is valid is then by ensuring that the same "n" is allocated. By forcing the same n, we avoid cases where the effective frequency slot of the media channel is invalid (that is, the resulting frequency slot cannot be described by its n and m parameters).

Maybe this is a too hard restriction, since a node (or even a centralized/combined RSA entity) can make sure that the resulting end to end (effective) frequency slot is valid, even if n is different locally. That means, the effective (end to end) frequency slot that characterizes the media channel is one and determined by its n and m, but are logical, in the sense that they are the result of the intersection of local (filters) freq slots which may have different freq. slots

For Figure Figure 15 the effective slot is valid by ensuring that the minimum m is greater than the requested m. The effective slot (intersection) is the lowest m (bottleneck).

For Figure Figure 16 the effective slot is valid by ensuring that it is valid at each hop in the upstream direction. The intersection needs to be computed. Invalid slots could result otherwise.

```
             |Path(m_req)   |                ^                |
             |--------->    |                #                |
             |              |                #                ^
            -^--------------^----------------#----------------#--
   Effective #              #                #                #
   FS n, m   # . . . . . . .#. . . . . . . . # . . . . . . . .# <-fixed
             #              #                #                #   n
            -v--------------v----------------#----------------#---
             |              |                #                v
             |              |                #          Resv  |
             |              |                v        <------ |
             |              |                |flowspec(n, m_a)|
             |              |       <--------|                |
             |              |  flowspec (n,  |
                   <--------|      min(m_a, m_b))
             flowspec (n,  |
               min(m_a, m_b, m_c))
```

       Figure 15: Distributed allocation with different m and same n

```
             |Path(m_req)  ^                |
             |--------->   #                |                 |
             |             #                ^                 ^
            -^-------------#----------------#-----------------#--------
   Effective #             #                #                 #
   FS n, m   #             #                #                 #
             #             #                #                 #
            -v-------------v----------------#-----------------#--------
             |             |                #                 v
             |             |                #          Resv   |
             |             |                v        <------- |
             |             |                |flowspec(n_a, m_a)
             |             |       <--------|                 |
             |             |  flowspec (FSb [intersect] FSa)
                  <--------|
            flowspec ([intersect] FSa,FSb,FSc)
```

    Figure 16: Distributed allocation with different m and different n

Note, when a media channel is bound to one OCh-P (i.e is a Network media channel), the EFS must be the one of the Och-P. The media channel setup by the LSP may contains the EFS of the network media channel EFS. This is an endpoint property, the egress and ingress SHOULD constrain the EFS to Och-P EFS .

5.6. Neighbor Discovery and Link Property Correlation

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.

5.7. 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 (Routing and Spectrum Assignment) 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.

5.7.1. 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.

5.7.1.1. 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.

5.7.1.2. 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.

5.7.1.3. 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.

5.8. 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.

5.8.1. 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.

5.8.2. 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.

5.8.3. 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.

5.8.4. 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.

```
<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 A&#151; 6.25GHz,
  where n is positive integer, such as 6.25GHz, 12.5GHz, 25GHz, 50GHz
  or 100GHz

<Available Slot Width Granularity> ::= m A&#151; 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 17: Routing Information model

6. Control Plane Requirements

The GMPLS based control plane of a flexi-grid networks provides aditional requirements to GMPLS. In this section the features to be covered by GMPLS signaling for flexi-grid are identified. [Editor's note: Only discussed requirements are included at this stage. Routing requirements will come in the next version]

6.1. Support for Media Channels

The control plane SHALL be able to support Media Channels, characterized by a single frequency slot. The representation of the Media Channel in the GMPLS Control plane is the so-called flexi-grid LSP. Since network media channels are media channels, an LSP may also be the control plane representation of a network media channel. Consequently, the control plane SHALL be able to support Network Media Channels.

The signaling procedure SHALL be able to configure the nominal central frequency (n) of a flexi-grid LSP.

The control plane protocols SHALL allow flexible range of values for the frequency slot width (m) parameter. Specifically, the control plane SHALL allow setting up a media channel with frequency slot width (m) ranging from a minimum of m=1 (12.5GHz) to a maximum of the entire C-band with a slot width granularity of 12.5GHz.

The signaling procedure of the GMPLS control plane SHALL be able to configure the minimum width (m) of a flexi-grid LSP. In adition, the control plane SHALL be able to configure local frecuency slots,

The control plane architecture SHOULD allow for the support of L-band and S-band

The signalling process of the control plane SHALL allow to collect the local frequency slot asigned at each link along the path

6.2. Support for Media Channel Resizing

The control plane SHALL allow resizing (grow or shrink) the frequency slot width of a media channel/network media channel. The resizing MAY imply resizing the local frequency slots along the path of the flexi-grid LSP.

6.3. Support for Logical Associations of multiple media channels

A set of media channels can be used to transport signals that have a logical association between them. The control plane architecture SHOULD allow multiple media channels to be logically associated. The control plane SHOULD allow the co-routing of a set of media channels logically associated

7. Security Considerations

TBD

8. Contributing Authors

Qilei Wang
ZTE
Ruanjian Avenue, Nanjing, China
wang.qilei@zte.com.cn

Malcolm Betts
ZTE
malcolm.betts@zte.com.cn

Xian Zhang
Huawei
zhang.xian@huawei.com

Cyril Margaria
Nokia Siemens Networks
St Martin Strasse 76, Munich, 81541, Germany
+49 89 5159 16934
cyril.margaria@nsn.com

Sergio Belotti
Alcatel Lucent
Optics CTO
Via Trento 30 20059 Vimercate (Milano) Italy
+39 039 6863033
sergio.belotti@alcatel-lucent.com

Yao Li
Nanjing University
wsliguotou@hotmail.com

Fei Zhang
ZTE
Zijinghua Road, Nanjing, China
zhang.fei3@zte.com.cn

Lei Wang
ZTE
East Huayuan Road, Haidian district, Beijing, China
wang.lei131@zte.com.cn

Guoying Zhang
China Academy of Telecom Research
No.52 Huayuan Bei Road, Beijing, China
zhangguoying@ritt.cn

Takehiro Tsuritani
KDDI R&D Laboratories Inc.
2-1-15 Ohara, Fujimino, Saitama, Japan
tsuri@kddilabs.jp

Lei Liu
KDDI R&D Laboratories Inc.
2-1-15 Ohara, Fujimino, Saitama, Japan
le-liu@kddilabs.jp

Eve Varma
Alcatel-Lucent
+1 732 239 7656
eve.varma@alcatel-lucent.com

Young Lee
Huawei

Jianrui Han
Huawei

Sharfuddin Syed
Infinera

Rajan Rao
Infinera

Marco Sosa
Infinera

Biao Lu
Infinera

Abinder Dhillon
Infinera

Felipe Jimenez Arribas
TelefA^3nica I+D

Andrew G. Malis
Verizon

Adrian Farrel
Old Dog Consulting

Daniel King
Old Dog Consulting

Huub van Helvoort

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Authors' Addresses

Oscar Gonzalez de Dios (editor)
Telefonica I+D
Don Ramon de la Cruz 82-84
Madrid 28045
Spain

Phone: +34913128832
Email: ogondio@tid.es

Ramon Casellas (editor)
CTTC
Av. Carl Friedrich Gauss n.7
Castelldefels Barcelona
Spain

Phone: +34 93 645 29 00
Email: ramon.casellas@cttc.es

Fatai Zhang
Huawei
Huawei Base, Bantian, Longgang District
Shenzhen 518129
China

Phone: +86-755-28972912
Email: zhangfatai@huawei.com

Xihua Fu
ZTE
Ruanjian Avenue
Nanjing
China

Email: fu.xihua@zte.com.cn

Daniele Ceccarelli
Ericsson
Via Calda 5
Genova
Italy

Phone: +39 010 600 2512
Email: daniele.ceccarelli@ericsson.com

Iftekhar Hussain
Infinera
140 Caspian Ct.
Sunnyvale 94089
USA

Phone: 408-572-5233
Email: ihussain@infinera.com