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Framework and Requirements for GMPLS-Based Control
of Flexi-Grid Dense Wavelength Division Multiplexing (DWDM) Networks

Abstract

To allow efficient allocation of optical spectral bandwidth for systems that have high bit-rates, the International Telecommunication Union Telecommunication Standardization Sector (ITU-T) has extended its Recommendations G.694.1 and G.872 to include a new Dense Wavelength Division Multiplexing (DWDM) grid by defining a set of nominal central frequencies, channel spacings, and the concept of the "frequency slot". In such an environment, a data-plane connection is switched based on allocated, variable-sized frequency ranges within the optical spectrum, creating what is known as a flexible grid (flexi-grid).

Given the specific characteristics of flexi-grid optical networks and their associated technology, this document defines a framework and the associated control-plane requirements for the application of the existing GMPLS architecture and control-plane protocols to the control of flexi-grid DWDM networks. The actual extensions to the GMPLS protocols will be defined in companion documents.

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Table of Contents

| | | |
|--------|--|----|
| 1. | Introduction | 4 |
| 2. | Terminology | 5 |
| 2.1. | Requirements Language | 5 |
| 2.2. | Abbreviations | 5 |
| 3. | Overview of Flexi-Grid Networks | 6 |
| 3.1. | Flexi-Grid in the Context of OTN | 6 |
| 3.2. | Flexi-Grid Terminology | 6 |
| 3.2.1. | Frequency Slots | 7 |
| 3.2.2. | Media-Layer Elements | 9 |
| 3.2.3. | Media Channels | 10 |
| 3.2.4. | Optical Tributary Signals | 10 |
| 3.2.5. | Composite Media Channels | 11 |
| 3.3. | Hierarchy in the Media Layer | 11 |
| 3.4. | Flexi-Grid Layered Network Model | 12 |
| 3.4.1. | DWDM Flexi-Grid Enabled Network Element Models | 13 |
| 4. | GMPLS Applicability | 14 |
| 4.1. | General Considerations | 14 |
| 4.2. | Consideration of TE Links | 14 |
| 4.3. | Consideration of LSPs in Flexi-Grid | 17 |
| 4.4. | Control-Plane Modeling of Network Elements | 22 |
| 4.5. | Media Layer Resource Allocation Considerations | 22 |
| 4.6. | Neighbor Discovery and Link Property Correlation | 26 |
| 4.7. | Path Computation, Routing and Spectrum Assignment (RSA) | 27 |
| 4.7.1. | Architectural Approaches to RSA | 28 |
| 4.8. | Routing and Topology Dissemination | 29 |
| 4.8.1. | Available Frequency Ranges (Frequency Slots) of DWDM Links | 29 |
| 4.8.2. | Available Slot Width Ranges of DWDM Links | 29 |
| 4.8.3. | Spectrum Management | 29 |
| 4.8.4. | Information Model | 30 |
| 5. | Control-Plane Requirements | 31 |
| 5.1. | Support for Media Channels | 31 |
| 5.1.1. | Signaling | 32 |
| 5.1.2. | Routing | 32 |
| 5.2. | Support for Media Channel Resizing | 33 |
| 5.3. | Support for Logical Associations of Multiple Media Channels | 33 |
| 5.4. | Support for Composite Media Channels | 33 |
| 5.5. | Support for Neighbor Discovery and Link Property Correlation | 34 |
| 6. | Security Considerations | 34 |
| 7. | Manageability Considerations | 35 |

| | |
|-----------------------------------|----|
| 8. References | 36 |
| 8.1. Normative References | 36 |
| 8.2. Informative References | 37 |
| Acknowledgments | 39 |
| Contributors | 39 |
| Authors' Addresses | 41 |

1. 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 and allocation considerations that have been defined in order to allow an efficient and flexible allocation and configuration of optical spectral bandwidth for systems that have high bit-rates.

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.

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, a media channel can transport more than one Optical Tributary Signal (OTSi), as defined later in this document.

A Wavelength Switched Optical Network (WSON), addressed in [RFC6163], is a term commonly used to refer to the application/deployment of a GMPLS-based control plane for the control (e.g., provisioning and recovery) of a fixed-grid Wavelength Division Multiplexing (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 Dense Wavelength Division Multiplexing (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.

2. Terminology

Further terminology specific to flexi-grid networks can be found in Section 3.2.

2.1. 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].

While [RFC2119] describes interpretations of these key words in terms of protocol specifications and implementations, they are used in this document to describe design requirements for protocol extensions.

2.2. Abbreviations

FS: Frequency Slot

FSC: Fiber-Switch Capable

LSR: Label Switching Router

NCF: Nominal Central Frequency

OCC: Optical Channel Carrier

OCh: Optical Channel

OCh-P: Optical Channel Payload

OTN: Optical Transport Network

OTSi: Optical Tributary Signal

OTSiG: OTSi Group is a set of OTSi

PCE: Path Computation Element

ROADM: Reconfigurable Optical Add/Drop Multiplexer

SSON: Spectrum-Switched Optical Network

SWG: Slot Width Granularity

3. Overview of Flexi-Grid Networks

3.1. Flexi-Grid in the Context of OTN

[G.872] describes, from a network level, the functional architecture of an OTN. It is decomposed into independent-layer networks with client/layer relationships among them. A simplified view of the OTN layers is shown in Figure 1.

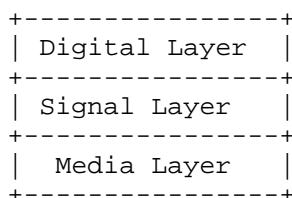


Figure 1: Generic OTN Overview

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.

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. This document mainly covers 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.

3.2. Flexi-Grid Terminology

This section presents the definitions of the terms used in flexi-grid networks. More details about these terms can be found in ITU-T Recommendations [G.694.1], [G.872], [G.870], [G.8080], and [G.959.1-2013].

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

3.2.1. Frequency Slots

This subsection is focused on the frequency slot and 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.
- o Nominal Central Frequency: Each of the allowed frequencies as per the definition of the flexible DWDM grid in [G.694.1]. The set of nominal central frequencies can be built using the following expression:

$$f = 193.1 \text{ THz} + n \times 0.00625 \text{ THz}$$

where 193.1 THz is the ITU-T "anchor frequency" for transmission over the C-band and 'n' is a positive or negative integer including 0.

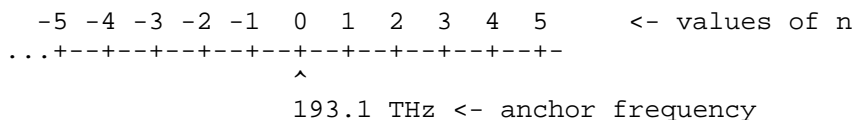


Figure 2: Anchor Frequency and Set of Nominal Central Frequencies

- o Nominal Central Frequency Granularity: The spacing between allowed nominal central frequencies. It is set to 6.25 GHz [G.694.1].
- o Slot Width Granularity (SWG): 12.5 GHz, as defined in [G.694.1].

- o Figure 4 shows the effect of combining two filters along a channel. The combination of Frequency Slot 1 and Frequency Slot 2 applied to the media channel is the effective frequency slot shown.

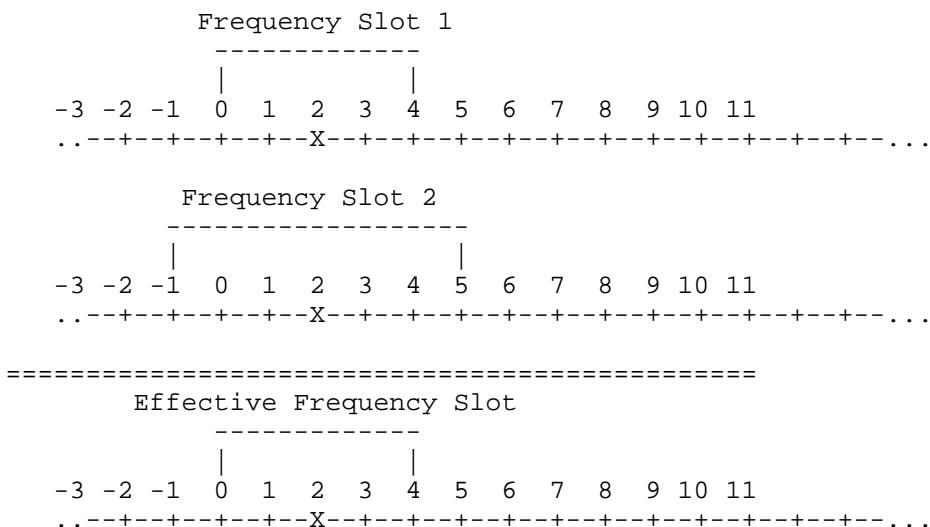


Figure 4: Effective Frequency Slot

3.2.2. Media-Layer Elements

- o Media Element: A media element directs an 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.
- o Media Channel Matrix: 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.

3.2.3. Media Channels

This section defines concepts such as the (network) media channel; the mapping to GMPLS constructs (i.e., LSP) is detailed in Section 4.

- o 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 frequency slot (an 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 filter.
- o Network Media Channel: Defined in [G.870] as a media channel that transports a single OTSi (defined in the next subsection).

3.2.4. Optical Tributary Signals

- o Optical Tributary Signal (OTSi): 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. To provide a connection between the OTSi source and the OTSi sink, the optical signal must be assigned to a network media channel (see also [G.959.1-2013]).
- o OTSi Group (OTSiG): The set of OTSi that are carried by a group of network media channels. Each OTSi is carried by one network media channel. From a management perspective, it SHOULD be possible to manage both the OTSiG and a group of network media channels as single entities.

3.2.5. Composite Media Channels

- o It is possible to construct an end-to-end media channel as a composite of more than one network media channel. A composite media channel carries a group of OTSi (i.e., OTSiG). Each OTSi is carried by one network media channel. This OTSiG is carried over a single fiber.
- o In this case, the effective frequency slots may be contiguous (i.e., there is no spectrum between them that can be used for other media channels) or non-contiguous.
- o It is not currently envisaged that such composite media channels may be constructed from slots carried on different fibers whether those fibers traverse the same hop-by-hop path through the network or not.
- o Furthermore, it is not considered likely that a media channel may be constructed from a different variation of slot composition on each hop. That is, the slot composition (i.e., the group of OTSi carried by the composite media channel) must be the same from one end of the media channel to the other, even if the specific slot for each OTSi and the spacing among slots may vary hop by hop.
- o How the signal is carried across such groups of network media channels is out of scope for this document.

3.3. Hierarchy in the Media Layer

In summary, the concept of the 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 respective (effective) frequency slots, and media channels are switched in media channel matrices. From the control and management perspective, a media channel can be logically split into network media channels.

In Figure 5, a media channel has been configured and dimensioned to support two network media channels, each of them carrying one OTSi.

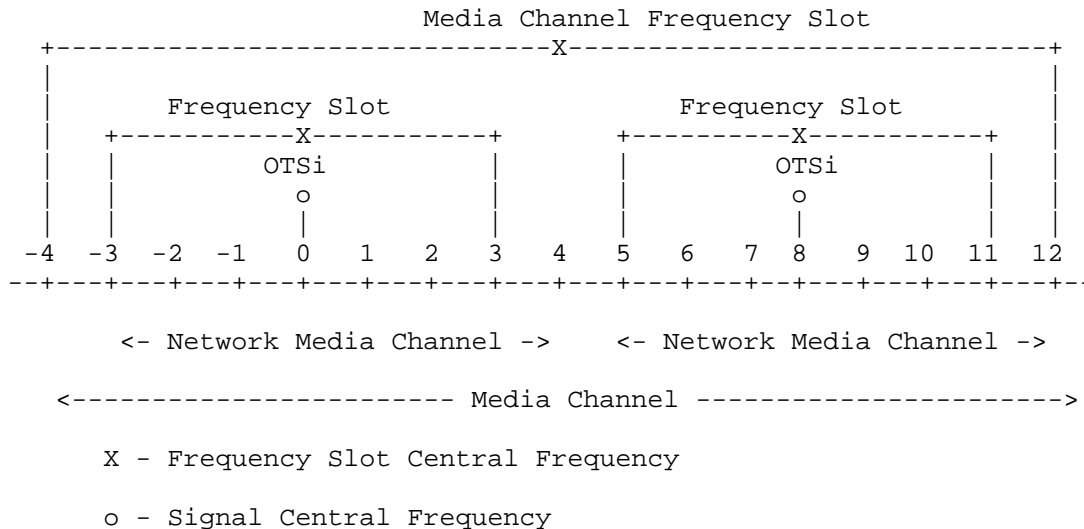
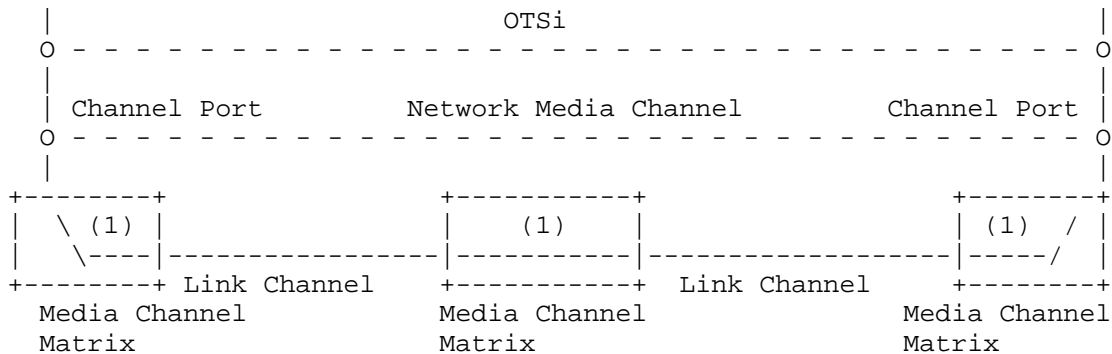


Figure 5: Example of Media Channel, Network Media Channels, and Associated Frequency Slots

3.4. Flexi-Grid Layered Network Model

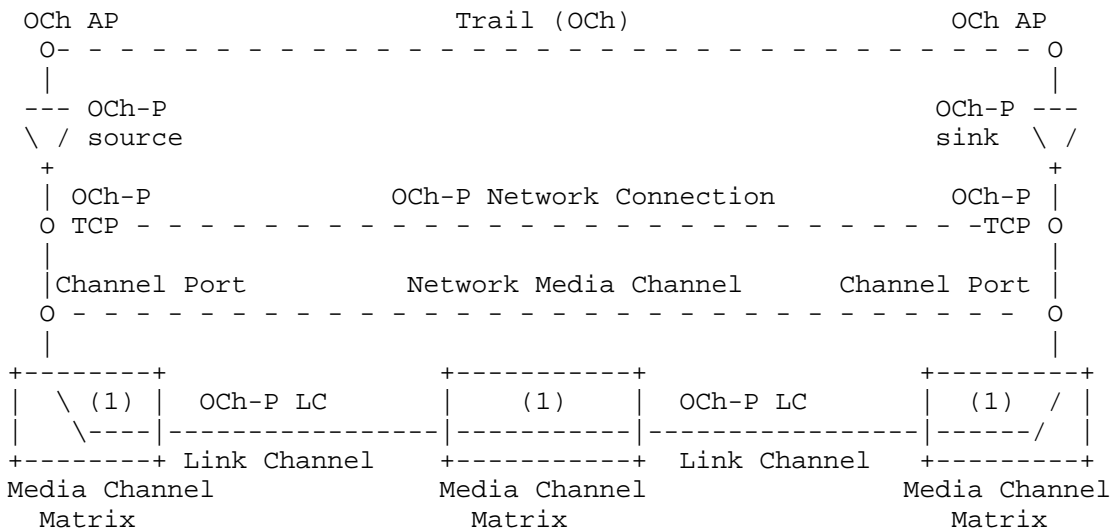
In the OTN layered network, the network media channel transports a single OTSi (see Figure 6).



The symbol (1) indicates a matrix channel

Figure 6: Simplified Layered Network Model

Note that a particular example of OTSi is the OCh-P. Figure 7 shows this specific example as defined in G.805 [G.805].



The symbol (1) indicates a matrix channel
 "LC" indicates a link connection

Figure 7: Layered Network Model According to G.805

3.4.1. DWDM Flexi-Grid Enabled Network Element Models

A flexible-grid network is constructed from subsystems that include WDM links, tunable transmitters, and receivers (i.e., media elements including media-layer switching elements that are media matrices), as well as electro-optical network elements. This is just the same as in a fixed-grid network, except that each element has flexible-grid characteristics.

As stated in Clause 7 of [G.694.1], the flexible DWDM grid has a nominal central frequency granularity of 6.25 GHz and a slot width granularity of 12.5 GHz. However, devices or applications that make use of the flexible grid might 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 is 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 where slot widths are a multiple of 25 GHz (by only requiring values of m that are even).

4. GMPLS Applicability

The goal of this section is to provide an insight into the application of GMPLS as a control mechanism in flexi-grid networks. Specific control-plane requirements for the support of flexi-grid networks are covered in Section 5. This framework is aimed at controlling the media layer within the OTN hierarchy and controlling the required adaptations of the signal layer. This document also defines the term "Spectrum-Switched Optical Network" (SSON) to refer to a flexi-grid enabled DWDM network that is controlled by a GMPLS or PCE control plane.

This section provides a mapping of the ITU-T G.872 architectural aspects to GMPLS and control-plane terms and also considers the relationship between the architectural concept or construct of a media channel and its control-plane representations (e.g., as a TE link, as defined in [RFC3945]).

4.1. General Considerations

The GMPLS control of the media layer deals with the establishment of media channels that are switched in media channel matrices. GMPLS labels are used to locally represent the media channel and its associated frequency slot. Network media channels are considered a particular case of media channels when the endpoints are transceivers (that is, the source and destination of an OTSi).

4.2. Consideration of TE Links

From a theoretical point of view, a fiber can be modeled as having a frequency slot that ranges from minus infinity to plus infinity. This representation helps us understand the relationship between frequency slots and ranges.

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

The association sequence of the three components (i.e., a filter, a fiber, and a filter) is a media channel in its most basic form. From the control-plane perspective, this may be modeled as a (physical) TE link with a contiguous optical spectrum. This can be represented by saying that the portion of spectrum available at time t_0 depends on which filters are placed at the ends of the fiber and how they have been configured. Once filters are placed, we have a one-hop media channel. In practical terms, associating a fiber with the terminating filters determines the usable optical spectrum.

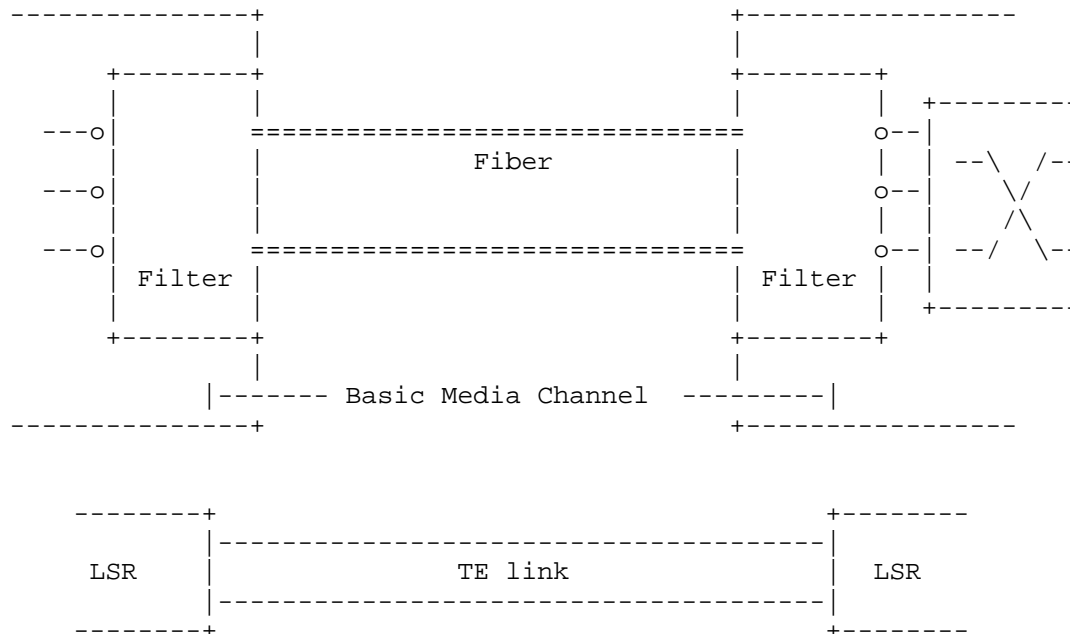


Figure 8: (Basic) Media Channel and TE Link

Additionally, when a cross-connect for a specific frequency slot is considered, the resulting media support of joining basic media channels is still a media channel, i.e., a longer association sequence of media elements and its effective frequency slot. In other words, it is possible to "concatenate" several media channels (e.g., patch on intermediate nodes) to create a single media channel.

The architectural construct resulting from the association sequence of basic media channels and media-layer matrix cross-connects can be represented as (i.e., corresponds to) a Label Switched Path (LSP) from a control-plane perspective.

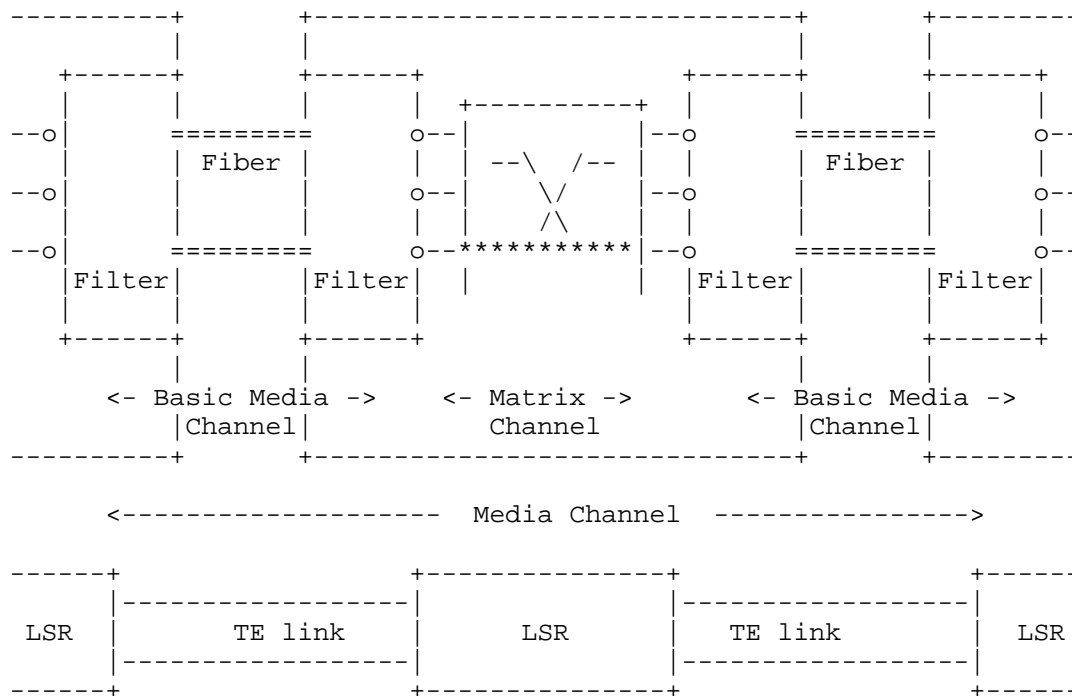


Figure 9: Extended Media Channel

Furthermore, if appropriate, the media channel can also be represented as a TE link or Forwarding Adjacency (FA) [RFC4206], augmenting the control-plane network model.

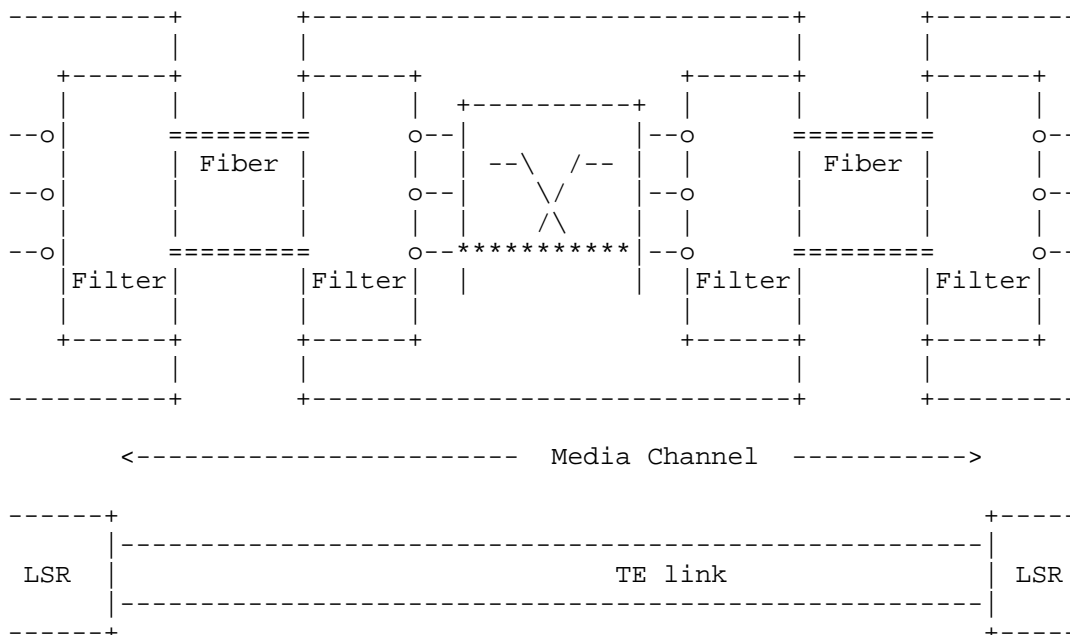


Figure 10: Extended Media Channel TE Link or FA

4.3. Consideration of LSPs in Flexi-Grid

The flexi-grid LSP is 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 (without considering the adaptation functions). 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 and egress nodes. The ports towards the client can still be represented as interfaces from the control-plane perspective.

Figure 11 shows an LSP routed between three 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 because it does not include (and cannot include) the transceivers.

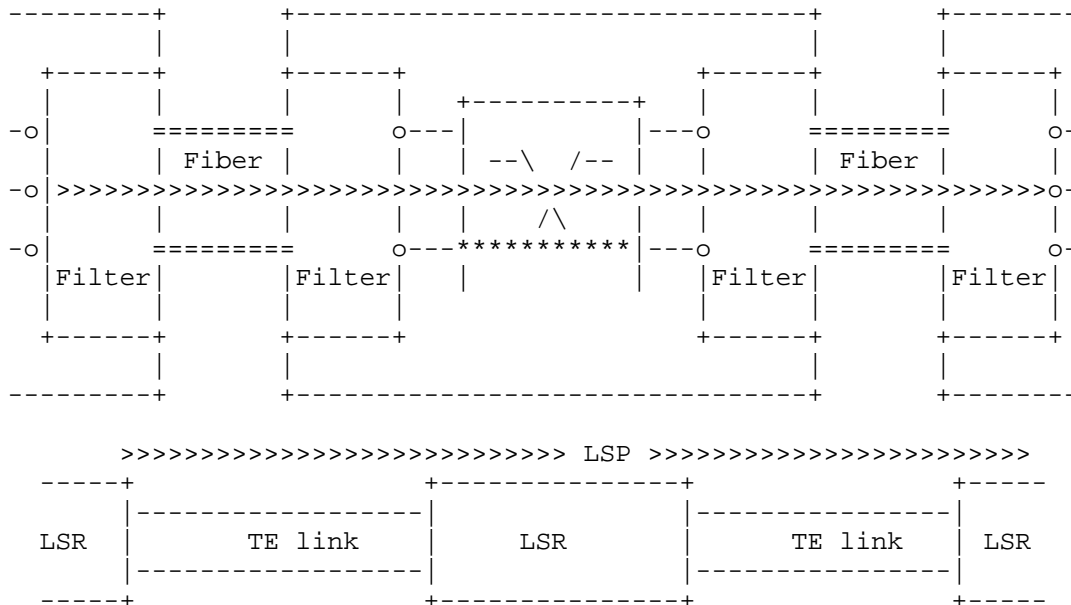


Figure 11: Flexi-Grid LSP Representing a Media Channel That Starts at the Filter of the Outgoing Interface of the Ingress LSR and Ends at the Filter of the Incoming Interface of the Egress LSR

In a third case, a network media channel is terminated on the filter ports of the ingress and egress nodes. This is defined in G.872 as an OTSi Network Connection. As can be seen from the figures, from a GMPLS modeling perspective there is no difference between these cases, but they are shown as distinct examples to highlight the differences in the data plane.

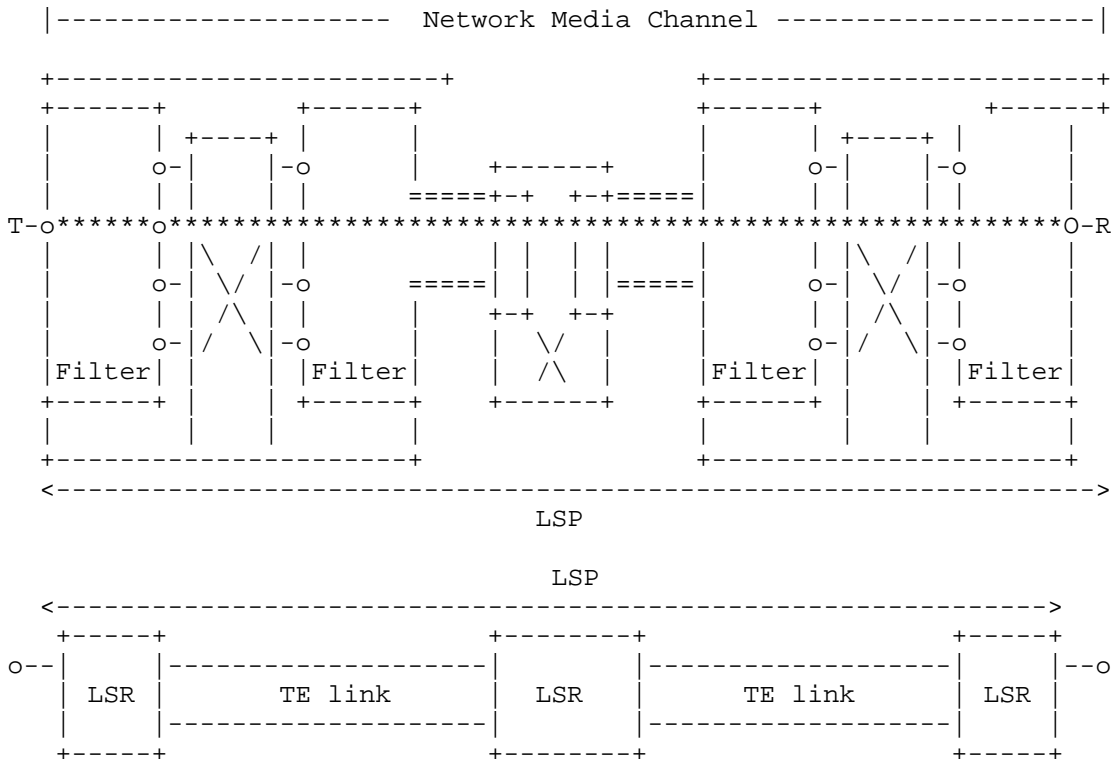


Figure 13: LSP Representing a Network Media Channel (OTSi Network Connection)

- o In the second case, each component network media channel is established using a separate control-plane LSP, and these LSPs are associated within the control plane so that the endpoints may see them as a single media channel.

4.4. Control-Plane Modeling of Network Elements

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

A set of common constraints can be defined:

- o Slot widths: 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 have not been allocated (i.e., are available). The relative grouping and distribution of available frequency ranges in a fiber are 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 could be from 50 GHz to 200 GHz.
 - * 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., 12.5 GHz) or integer multiples of 12.5 GHz.

4.5. 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" end-to-end frequency slot. The establishment of an LSP is related to the establishment of the media channel and the configuration of the effective frequency slot.

A "service request" is characterized (at a minimum) by its required effective slot width. This does not preclude the request from adding additional constraints, such as also imposing the nominal central frequency. A given effective frequency slot may be requested for the media channel in the control-plane LSP setup messages, and a specific frequency slot can be requested on any specific hop of the LSP setup. Regardless of the actual encoding, the LSP setup message specifies a minimum effective frequency slot width that needs to be fulfilled in order to successfully establish the requested LSP.

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, it must be possible to determine the end-to-end values of the n and m parameters. We refer to this by saying that the "effective frequency slot of the media channel or LSP must be valid".

In GMPLS, the requested effective frequency slot is represented to the TSpec present in the RSVP-TE Path message, and the effective frequency slot is mapped to the FlowSpec carried in the RSVP-TE Resv message.

In GMPLS-controlled systems, the switched element corresponds to the 'label'. In flexi-grid, the switched element is a frequency slot, and the label represents a frequency slot. Consequently, the label in flexi-grid conveys the necessary information to obtain the frequency slot characteristics (i.e., central frequency and slot width: the n and m parameters). The frequency slot is locally identified by the label.

The local frequency slot may change at each hop, given hardware constraints and capabilities (e.g., a given node might not support the finest granularity). This means that the values of n and m may change at each hop. As long as a given downstream node allocates enough optical spectrum, m can be different along the path. This covers the issue where media matrices can have different slot width granularities. Such variations in the local value of m will appear in the allocated label that encodes the frequency slot as well as in the FlowSpec that describes the flow.

Different operational modes can be considered. For Routing and Spectrum Assignment (RSA) with explicit label control, and for Routing and Distributed Spectrum Assignment (R+DSA), the GMPLS signaling procedures are similar to those described in Section 4.1.3 of [RFC6163] for Routing and Wavelength Assignment (RWA) and for Routing and Distributed Wavelength Assignment (R+DWA). The main difference is that the label set specifies the available nominal central frequencies that meet the slot width requirements of the LSP.

The intermediate nodes use the control plane to 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 an LSP to assign the proper frequency resource. Except for 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 for WSON as described in Section 6.1 of [RFC6163].

Regarding how a GMPLS control plane can assign n and m hop by hop along the path of an LSP, different cases can apply:

- a. n and m can both change. It is the effective frequency slot that matters; it needs to remain valid along the path.
- b. m can change, but n needs to remain the same along the path. This ensures that the nominal central frequency stays the same, but the width of the slot can vary along the path. Again, the important thing is that the effective frequency slot remains valid and satisfies the requested parameters along the whole path of the LSP.
- c. n and m need to be unchanging along the path. This ensures that the frequency slot is well known from end to end and is a simple way to ensure that the effective frequency slot remains valid for the whole LSP.
- d. n can change, but m needs to remain the same along the path. This ensures that the effective frequency slot remains valid but also allows the frequency slot to be moved within the spectrum from hop to hop.

The selection of a path that ensures n and m continuity can be delegated to a dedicated entity such as a Path Computation Element (PCE). Any constraint (including frequency slot and width granularities) can be taken into account during path computation. Alternatively, A PCE can compute a path, leaving the actual frequency slot assignment to be done, for example, with a distributed (signaling) procedure:

- o Each downstream node ensures that m is \geq requested $_m$.
- o A downstream node cannot foresee what an upstream node will allocate. A way to ensure that the effective frequency slot is valid along the length of the LSP is to ensure that the same value of n is allocated at each hop. By forcing the same value of 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).

- o This may be too restrictive, since a node (or even a centralized/combined RSA entity) may be able to ensure that the resulting end-to-end effective frequency slot is valid, even if n varies locally. That means that the effective frequency slot that characterizes the media channel from end to end is consistent and is determined by its n and m values but that the effective frequency slot and those values are logical (i.e., do not map "direct" to the physically assigned spectrum) in the sense that they are the result of the intersection of locally assigned frequency slots applicable at local components (such as filters), each of which may have different frequency slots assigned to them.

As shown in Figure 15, the effective slot is made valid by ensuring that the minimum m is greater than the requested m. The effective slot (intersection) is the lowest m (bottleneck).

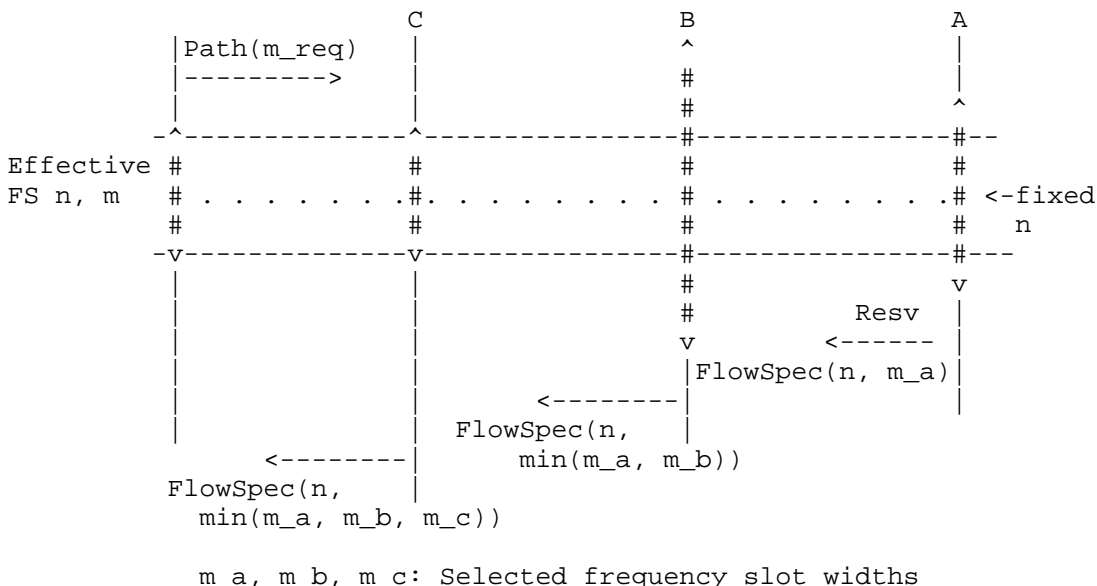


Figure 15: Distributed Allocation with Different m and Same n

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

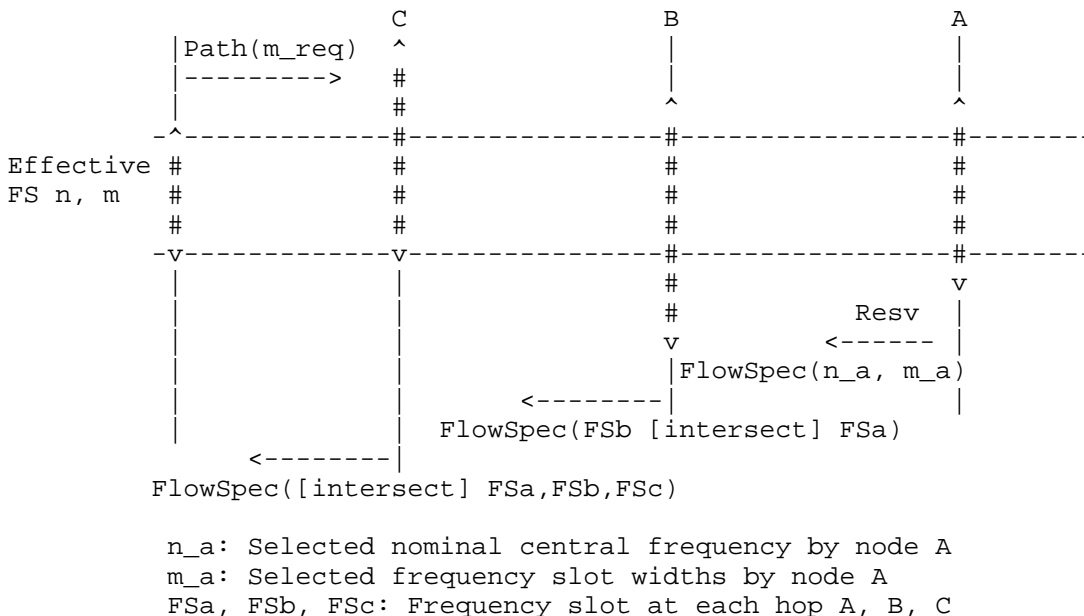


Figure 16: Distributed Allocation with Different m and Different n

Note that when a media channel is bound to one OTSi (i.e., is a network media channel), the effective FS must be the frequency slot of the OTSi. The media channel set up by the LSP may contain the effective FS of the network media channel effective FS. This is an endpoint property; the egress and ingress have to constrain the effective FS to be the OTSi effective FS.

4.6. Neighbor Discovery and Link Property Correlation

There are potential interworking problems between fixed-grid DWDM nodes and flexi-grid DWDM nodes. Additionally, even two flexi-grid nodes may have different grid properties, leading to link property conflict and resulting in limited interworking.

Devices or applications that make use of flexi-grid might not be able to support every possible slot width. In other words, different applications may be defined where each supports a different grid granularity. In this case, the link between two optical nodes with

different grid granularities must be configured to align with the larger of both granularities. Furthermore, different nodes may have different slot width tuning ranges.

In summary, in a DWDM link between two nodes, at a minimum, the following properties need to be negotiated:

- o Grid capability (channel spacing) - Between fixed-grid and flexi-grid nodes.
- o Grid granularity - Between two flexi-grid nodes.
- o Slot width tuning range - Between two flexi-grid nodes.

4.7. Path Computation, Routing and Spectrum Assignment (RSA)

In WSON, if there is no (available) wavelength converter in an optical network, an LSP is subject to the "wavelength continuity constraint" (see Section 4 of [RFC6163]). Similarly, in flexi-grid, if the capability to shift or convert an allocated frequency slot is absent, the LSP is subject to the "spectrum continuity constraint".

Because of the limited availability of spectrum converters (in what is called a "sparse translucent optical network"), the spectrum continuity constraint always has to 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 an LSP. Hence, when a route is computed, the spectrum assignment process determines the central frequency and slot width based on the following:

- o the requested slot width
- o the information regarding the transmitter and receiver capabilities, including the availability of central frequencies and their slot width granularity
- o the information regarding available frequency slots (frequency ranges) and available slot widths of the links traversed along the route

4.7.1. Architectural Approaches to RSA

Similar to RWA for fixed grids [RFC6163], 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.

Note that all of these models allow the concept of a composite media channel supported by a single control-plane LSP or by a set of associated LSPs.

4.7.1.1. Combined RSA (R&SA)

In this case, a computation entity performs both routing and frequency slot assignment. The computation entity needs access to detailed network information, e.g., the connectivity topology of the nodes and links, available frequency ranges on each link, and node capabilities.

The computation entity could reside on a dedicated PCE server, in the provisioning application that requests the service, or on the ingress node.

4.7.1.2. 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 needs the connectivity topology to compute the proper routes. The second entity needs information about the available frequency ranges of the links and the capabilities of the nodes in order to assign the spectrum.

4.7.1.3. Routing and Distributed SA (R+DSA)

In this case, an 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 that meet the spectrum continuity constraint need to be collected hop by hop along the route. This procedure can be implemented by the GMPLS signaling protocol.

4.8. Routing and Topology Dissemination

In the case of the combined RSA architecture, the computation entity needs 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, while spectrum assignment is performed based on the available frequency ranges of the links. The computation entity may get the detailed network information via the GMPLS routing protocol.

For WSON, the connectivity topology and node capabilities can be advertised by the GMPLS routing protocol (refer to Section 6.2 of [RFC6163]). Except for wavelength-specific availability information, the information for flexi-grid is the same as for WSON and can equally be distributed by the GMPLS routing protocol.

This section analyzes the necessary changes to link information required by flexible grids.

4.8.1. Available Frequency Ranges (Frequency 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 a granularity of 6.25 GHz. Different LSPs could make use of different slot widths on the same link. Hence, the available frequency ranges need to be advertised.

4.8.2. Available Slot Width Ranges of DWDM Links

The available slot width ranges need to be advertised in combination with the available frequency ranges, so that the computing entity can verify whether an LSP with a given slot width can be set up or not. This 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 what is strictly needed by the LSP.

4.8.3. Spectrum Management

The total available spectrum on a fiber can be described as a resource that can be partitioned. For example, a part of the spectrum could be assigned to a third party to manage, or parts of the spectrum could be assigned by the operator for different classes of traffic. This partitioning creates the impression that the spectrum is a hierarchy in view of the management plane and the control plane: each partition could itself be partitioned. However,

the hierarchy is created purely within a management system; it defines a hierarchy of access or management rights, but there is no corresponding resource hierarchy within the fiber.

The end of the fiber is a link end and presents a fiber port that represents all of the spectrum available on the fiber. Each spectrum allocation appears as a Link Channel Port (i.e., frequency slot port) within the fiber. Thus, while there is a hierarchy of ownership (the Link Channel Port and corresponding LSP are located on a fiber and therefore are associated with a fiber port), there is no continued nesting hierarchy of frequency slots within larger frequency slots. In its way, this mirrors the fixed-grid behavior where a wavelength is associated with a fiber port but cannot be subdivided even though it is a partition of the total spectrum available on the fiber.

4.8.4. Information Model

This section defines an information model to describe the data that represents the capabilities and resources available in a flexi-grid network. It is not a data model and is not intended to limit any protocol solution such as an encoding for an IGP. For example, information required for routing and 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 is left for further study in an IGP encoding document.

Fixed DWDM 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. Thus, the information model needs to enable:

- o the exchange of information to enable RSA in a flexi-grid network
- o the representation of a fixed-grid device participating in a flexi-grid network
- o full interworking of fixed-grid and flexible-grid devices within the same network
- o interworking of flexible-grid devices with different capabilities

The information model is represented using the Routing Backus-Naur Format (RBNF) as defined in [RFC5511].

```
<Available Spectrum> ::=
  <Available Frequency Range-List>
  <Available NCFs>
  <Available Slot Widths>
```

where

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

```
<Available Frequency Range> ::=
  ( <Start NCF> <End NCF> ) |
  <FS defined by (n, m) containing contiguous available NCFs>
```

and

```
<Available NCFs> ::=
  <Available NCF Granularity> [<Offset>]
  -- Subset of supported n values given by p x n + q
  -- where p is a positive integer
  -- and q (offset) belongs to 0,...,p-1.
```

and

```
<Available Slot Widths> ::=
  <Available Slot Width Granularity>
  <Min Slot Width>
  -- given by j x 12.5 GHz, with j a positive integer
  <Max Slot Width>
  -- given by k x 12.5 GHz, with k a positive integer (k >= j)
```

Figure 17: Routing Information Model

5. Control-Plane Requirements

The control of flexi-grid networks places additional requirements on the GMPLS protocols. This section summarizes those requirements for signaling and routing.

5.1. 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 will also be able to support network media channels.

5.1.1. Signaling

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

The signaling procedure SHALL allow a 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 $m = 1$ (12.5 GHz) to a maximum of the entire C-band (the wavelength range 1530 nm to 1565 nm, which corresponds to the amplification range of erbium-doped fiber amplifiers) with a slot width granularity of 12.5 GHz.

The signaling procedure SHALL be able to configure the minimum width (m) of a flexi-grid LSP. In addition, the signaling procedure SHALL be able to configure local frequency slots.

The control-plane architecture SHOULD allow for the support of the L-band (the wavelength range 1565 nm to 1625 nm) and the S-band (the wavelength range 1460 nm to 1530 nm).

The signaling process SHALL be able to collect the local frequency slot assigned at each link along the path.

The signaling procedures SHALL support all of the RSA architectural models (R&SA, R+SA, and R+DSA) within a single set of protocol objects, although some objects may only be applicable within one of the models.

5.1.2. Routing

The routing protocol will support all functions described in [RFC4202] and extend them to a flexi-grid data plane.

The routing protocol SHALL distribute sufficient information to compute paths to enable the signaling procedure to establish LSPs as described in the previous sections. This includes, at a minimum, the data described by the information model in Figure 17.

The routing protocol SHALL update its advertisements of available resources and capabilities as the usage of resources in the network varies with the establishment or teardown of LSPs. These updates SHOULD be amenable to damping and thresholds as in other traffic engineering routing advertisements.

The routing protocol SHALL support all of the RSA architectural models (R&SA, R+SA, and R+DSA) without any configuration or change of behavior. Thus, the routing protocols SHALL be agnostic to the computation and signaling model that is in use.

5.2. Support for Media Channel Resizing

The signaling procedures SHALL allow the resizing (growing or shrinking) of the frequency slot width of a media channel or network media channel. The resizing MAY imply resizing the local frequency slots along the path of the flexi-grid LSP.

The routing protocol SHALL update its advertisements of available resources and capabilities as the usage of resources in the network varies with the resizing of LSPs. These updates SHOULD be amenable to damping and thresholds as in other traffic engineering routing advertisements.

5.3. 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 that are logically associated.

5.4. Support for Composite Media Channels

As described in Sections 3.2.5 and 4.3, a media channel may be composed of multiple network media channels.

The signaling procedures SHOULD include support for signaling a single control-plane LSP that includes information about multiple network media channels that will comprise the single compound media channel.

The signaling procedures SHOULD include a mechanism to associate separately signaled control-plane LSPs so that the endpoints may correlate them into a single compound media channel.

The signaling procedures MAY include a mechanism to dynamically vary the composition of a composite media channel by allowing network media channels to be added to or removed from the whole.

The routing protocols MUST provide sufficient information for the computation of paths and slots for composite media channels using any of the three RSA architectural models (R&SA, R+SA, and R+DSA).

5.5. Support for Neighbor Discovery and Link Property Correlation

The control plane MAY include support for neighbor discovery such that a flexi-grid network can be constructed in a "plug-and-play" manner. Note, however, that in common operational practice, validation processes are used rather than automatic discovery.

The control plane SHOULD allow the nodes at opposite ends of a link to correlate the properties that they will apply to the link. Such a correlation SHOULD include at least the identities of the nodes and the identities that they apply to the link. Other properties, such as the link characteristics described for the routing information model in Figure 17, SHOULD also be correlated.

Such neighbor discovery and link property correlation, if provided, MUST be able to operate in both an out-of-band and an out-of-fiber control channel.

6. Security Considerations

The control-plane and data-plane aspects of a flexi-grid system are fundamentally the same as a fixed-grid system, and there is no substantial reason to expect the security considerations to be any different.

A good overview of the security considerations for a GMPLS-based control plane can be found in [RFC5920].

[RFC6163] includes a section describing security considerations for WSON, and it is reasonable to infer that these considerations apply and may be exacerbated in a flexi-grid SSON system. In particular, the detailed and granular information describing a flexi-grid network and the capabilities of nodes in that network could put stress on the routing protocol or the out-of-band control channel used by the protocol. An attacker might be able to cause small variations in the use of the network or the available resources (perhaps by modifying the environment of a fiber) and so trigger the routing protocol to make new flooding announcements. This situation is explicitly mitigated in the requirements for the routing protocol extensions where it is noted that the protocol must include damping and configurable thresholds as already exist in the core GMPLS routing protocols.

7. Manageability Considerations

GMPLS systems already contain a number of management tools:

- o MIB modules exist to model the control-plane protocols and the network elements [RFC4802] [RFC4803], and there is early work to provide similar access through YANG. The features described in these models are currently designed to represent fixed-label technologies such as optical networks using the fixed grid; extensions may be needed in order to represent bandwidth, frequency slots, and effective frequency slots in flexi-grid networks.
- o There are protocol extensions within GMPLS signaling to allow control-plane systems to report the presence of faults that affect LSPs [RFC4783], although it must be carefully noted that these mechanisms do not constitute an alarm mechanism that could be used to rapidly propagate information about faults in a way that would allow the data plane to perform protection switching. These mechanisms could easily be enhanced with the addition of technology-specific reason codes if any are needed.
- o The GMPLS protocols, themselves, already include fault detection and recovery mechanisms (such as the PathErr and Notify messages in RSVP-TE signaling as used by GMPLS [RFC3473]). It is not anticipated that these mechanisms will need enhancement to support flexi-grid, although additional reason codes may be needed to describe technology-specific error cases.
- o [RFC7260] describes a framework for the control and configuration of data-plane Operations, Administration, and Maintenance (OAM). It would not be appropriate for the IETF to define or describe data-plane OAM for optical systems, but the framework described in RFC 7260 could be used (with minor protocol extensions) to enable data-plane OAM that has been defined by the originators of the flexi-grid data-plane technology (the ITU-T).
- o The Link Management Protocol (LMP) [RFC4204] is designed to allow the two ends of a network link to coordinate and confirm the configuration and capabilities that they will apply to the link. LMP is particularly applicable to optical links, where the characteristics of the network devices may considerably affect how the link is used and where misconfiguration or mis-fibering could make physical interoperability impossible. LMP could easily be extended to collect and report information between the endpoints of links in a flexi-grid network.

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