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A Framework for the Control of Wavelength Switched Optical Networks (WSON) with Impairments

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Abstract

The operation of optical networks requires information on the physical characterization of optical network elements, subsystems, devices, and cabling. These physical characteristics may be important to consider when using a GMPLS control plane to support path setup and maintenance. This document discusses how the definition and characterization of optical fiber, devices, subsystems, and network elements contained in various ITU-T recommendations can be combined with GMPLS control plane protocols and mechanisms to support Impairment Aware Routing and Wavelength Assignment (IA-RWA) in optical networks.

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1. Introduction

As an optical signal progresses along its path it may be altered by the various physical processes in the optical fibers and devices it encounters. When such alterations result in signal degradation, we usually refer to these processes as "impairments". An overview of some critical optical impairments and their routing (path selection) implications can be found in [RFC4054]. Roughly speaking, optical impairments accumulate along the path (without 3R regeneration) traversed by the signal. They are influenced by the type of fiber used, the types and placement of various optical devices and the presence of other optical signals that may share a fiber segment along the signal's path. The degradation of the optical signals due to impairments can result in unacceptable bit error rates or even a complete failure to demodulate and/or detect the received signal. Therefore, path selection in any WSON requires consideration of optical impairments so that the signal will be propagated from the network ingress point to the egress point with an acceptable signal quality.

Some optical subnetworks are designed such that over any path the degradation to an optical signal due to impairments never exceeds prescribed bounds. This may be due to the limited geographic extent of the network, the network topology, and/or the quality of the fiber and devices employed. In such networks the path selection problem reduces to determining a continuous wavelength from source to destination (the Routing and Wavelength Assignment problem). These networks are discussed in [WSON-Frame]. In other optical networks, impairments are important and the path selection process must be impairment-aware.

Although [RFC4054] describes a number of key optical impairments, a more complete description of optical impairments and processes can be found in the ITU-T Recommendations. Appendix A of this document provides an overview of the extensive ITU-T documentation in this area.

The benefits of operating networks using the Generalized Multiprotocol Label Switching (GMPLS) control plane is described in [RFC3945]. The advantages of using a path computation element (PCE) to perform complex path computations are discussed in [RFC4655].

Based on the existing ITU-T standards covering optical characteristics (impairments) and the knowledge of how the impact of impairments may be estimated along a path, this document provides a framework for impairment aware path computation and establishment utilizing GMPLS protocols and the PCE architecture. As in the impairment free case covered in [WSON-Frame], a number of different control plane architectural options are described.

2. Motivation

There are deployment scenarios for WSON networks where not all possible paths will yield suitable signal quality. There are multiple reasons behind this choice; here below is a non-exhaustive list of examples:

- WSON is evolving using multi-degree optical cross connects in a way that network topologies are changing from rings (and interconnected rings) to a full mesh. Adding network equipment such as amplifiers or regenerators, to make all paths feasible, leads to an over-provisioned network. Indeed, even with over provisioning, the network could still have some infeasible paths.

- Within a given network, the optical physical interface may change over the network life, e.g., the optical interfaces might be upgraded to higher bit-rates. Such changes could result in paths being unsuitable for the optical signal. Although the same considerations may apply to other network equipment upgrades, the optical physical interfaces are a typical case because they are typically provisioned at various stages of the network's life span as needed by traffic demands.

- There are cases where a network is upgraded by adding new optical cross connects to increase network flexibility. In such cases existing paths will have their feasibility modified while new paths will need to have their feasibility assessed.

Not having an impairment aware control plane for such networks will require a more complex network design phase that has to also take into account evolving network status in term of equipments and traffic. Moreover, network operations such as path establishment, will require significant pre-design via non-control plane processes resulting in significantly slower network provisioning.

3. Impairment Aware Optical Path Computation

The basic criteria for path selection is whether one can successfully transmit the signal from a transmitter to a receiver within a prescribed error tolerance, usually specified as a maximum permissible bit error ratio (BER). This generally depends on the nature of the signal transmitted between the sender and receiver and the nature of the communications channel between the sender and receiver. The optical path utilized (along with the wavelength) determines the communications channel.

The optical impairments incurred by the signal along the fiber and at each optical network element along the path determine whether the BER performance or any other measure of signal quality can be met for a signal on a particular end-to-end path.

3.1. Optical Network Requirements and Constraints

This section examines the various optical network requirements and constraints that an impairment aware optical control plane may have to operate under. These requirements and constraints motivate the IA-RWA architectural alternatives to be presented in the following section. We can break the different optical networks contexts up along two main criteria: (a) the accuracy required in the estimation of impairment effects, and (b) the constraints on the impairment estimation computation and/or sharing of impairment information.

3.1.1. Categories of Impairment Aware Computation

A. No concern for impairments or Wavelength Continuity Constraints

This situation is covered by existing GMPLS with local wavelength (label) assignment.

B. No concern for impairments but Wavelength Continuity Constraints

This situation is applicable to networks designed such that every possible path is valid for the signal types permitted on the network. In this case impairments are only taken into account during network design and after that, for example during optical path computation,

they can be ignored. This is the case discussed in [WSON-Frame] where impairments may be ignored by the control plane.

C. Approximated Impairment Estimation

This situation is applicable to networks in which impairment effects need to be considered but there is sufficient margin such that they can be estimated via approximation techniques such as link budgets and dispersion[G.680],[G.sup39]. The viability of optical paths for a particular class of signals can be estimated using well defined approximation techniques [G.680], [G.sup39]. Also, adding or removing an optical signal on the path will not render any of the existing signals in the network as non-viable. For example, one form of non-viability is the occurrence of transients in existing links of sufficient magnitude to impact the BER of those existing signals.

Much work at ITU-T has gone into developing impairment models at this and more detailed levels. Impairment characterization of network elements could then may be used to calculate which paths are conformant with a specified BER for a particular signal type. In such a case, we can combine the impairment aware (IA) path computation with the RWA process to permit more optimal IA-RWA computations. Note, the IA path computation may also take place in a separate entity, i.e., a PCE.

D. Detailed Impairment Computation

This situation is applicable to networks in which impairment effects must be more accurately computed. For these networks, a full computation and evaluation of the impact to any existing paths needs to be performed prior to the addition of a new path. This scenario is outside the scope of this document.

3.1.2. Impairment Computation and Information Sharing Constraints

In GMPLS, information used for path computation is standardized for distribution amongst the elements participating in the control plane and any appropriately equipped PCE can perform path computation. For optical systems this may not be possible. This is typically due to only portions of an optical system being subject to standardization. In ITU-T recommendations [G.698.1] and [G.698.2] which specify single channel interfaces to multi-channel DWDM systems only the single channel interfaces (transmit and receive) are specified while the multi-channel links are not standardized. These DWDM links are referred to as "black links" since their details are not generally

available. Note however the overall impact of a black link at the single channel interface points typically can be characterized [G.698.1] and [G.698.2].

Typically a vendor might use proprietary impairment models for DWDM spans and to estimate the validity of optical paths. For example, models of optical nonlinearities are not currently standardized. Vendors may also choose not to publish impairment details for links or a set of network elements in order not to divulge their optical system designs.

In general, the impairment estimation/validation of an optical path for optical networks with "black links" (path) could not be performed by a general purpose impairment aware (IA) computation entity since it would not have access to or understand the "black link" impairment parameters. However, impairment estimation (optical path validation) but could be performed by a vendor specific impairment aware computation entity. Such a vendor specific IA computation, could utilize standardized impairment information imported from other network elements in these proprietary computations. In section 3.2.

In the following we will use the term "black links" to describe these computation and information sharing constraints in optical networks. From the control plane perspective we have the following options:

A. The vendor in control of the "black links" can furnish a list of all viable paths between all viable node pairs to a computational entity. This information would be particularly useful as an input to RWA optimization to be performed by another computation entity. The difficulty here is for larger networks such a list of paths along with any wavelength constraints could get unmanageably large.

B. The vendor in control of the "black links" could furnish a PCE like entity that would furnish a list of viable paths/wavelengths between two requested nodes. This is useful as an input to RWA optimizations and can reduce the scaling issue previously mentioned. Such a PCE like entity would not need to perform a full RWA computation, i.e., it would not need to take into account current wavelength availability on links. Such an approach may require PCEP extensions for both the request and response information.

C. The vendor in control of the "black links" can furnish a PCE that performs full IA-RWA services. The difficulty is this requires the one vendor to also become the sole source of all RWA optimization algorithms and such.

In all the above cases it would be the responsibility of the vendor in control of the "black links" to import the shared impairment information from the other NEs via the control plane or other means as necessary.

3.1.3. Impairment Estimation Functional Blocks

The Impairment Estimation process can be modeled by the following functional blocks. These blocks are independent of any Control Plane architecture, that is, they can be implemented by the same or by different control plane functional blocks.

```
                                              +------------------+
    +------------+        +-----------+    |  +------------+ |
    |            |        |           |    |  |            | |
    | Optical    |        | Optical   |    |  | Optical    | |
    | Interface  |------->| Path      |--->|  | Channel    | |
    | (Transmit/ |        |           |    |  | Estimation | |
    |  Receive)  |        |           |    |  |            | |
    +------------+        +-----------+    |  +------------+ |
                                           |        ||       |
                                           |        ||       |
                                           |    Estimation   |
                                           |        ||       |
                                           |        \/       |
                                           |  +------------+ |
                                           |  |  BER /     | |
                                           |  |  Q Factor  | |
                                           |  +------------+ |
                                           +------------------+
```

Starting from functional block on the left the Optical Interface represents where the optical signal is transmitted or received and defines the properties at the end points path. For WSON even the case with no IA has to consider a minimum set of interface characteristics. As an example, the document [G.698.1] reports the full set of those parameters for certain interfaces. In this function only a significant subset of those parameters would be considered. In addition transmit and receive interface might consider a different subset of properties.

The block "Optical Path" represents all kinds of impairments affecting a wavelength as it traverses the networks through links and nodes. In the case where the control plane has no IA this block will not be present. Otherwise, this function must be implemented in some

way via the control plane. Options for this will be given in the next section on control plane architectural alternatives.

The last block implements the decision function for path feasibility. Depending on the IA level of approximation this function can be more or less complex. For example in case of no IA only the signal class compatibility will be verified.

3.2. IA-RWA Computing and Control Plane Architectures

From a control plane point of view optical impairments are additional constraints to the impairment-free RWA process described in [WSON-Frame]. In impairment aware routing and wavelength assignment (IA-RWA), there are conceptually three general classes of processes to be considered: Routing (R), Wavelength Assignment (WA), and Impairment Validation (estimation) (IV).

Impairment validation may come in many forms, and maybe invoked at different levels of detail in the IA-RWA process. From a process point of view we will consider the following three forms of impairment validation:

o IV-Candidates

In this case an Impairment Validation (IV) process furnishes a set of paths between two nodes along with any wavelength restrictions such that the paths are valid with respect to optical impairments. These paths and wavelengths may not be actually available in the network due to its current usage state. This set of paths would be returned in response to a request for a set of at most K valid paths between two specified nodes. Note that such a process never directly discloses optical impairment information.

o IV-Detailed Verification

In this case an IV process is given a particular path and wavelength through an optical network and is asked to verify whether the overall quality objectives for the signal over this path can be met. Note that such a process never directly discloses optical impairment information.

o IV-Distributed

In this distributed IV process impairment approximate degradation measures such as OSNR, dispersion, DGD, etc. are accumulated along the path via a signaling like protocol. When the accumulated measures reach the destination node a decision on the impairment validity of

the path can be made. Note that such a process would entail revealing an individual network element's impairment information.

The following subsections present three major classes of IA-RWA path computation architectures and their respective advantages and disadvantages.

3.2.1. Combined Routing, WA, and IV

From the point of view of optimality, the "best" IA-RWA solutions can be achieved if the path computation entity (PCE) can conceptually/algorithmically combine the processes of routing, wavelength assignment and impairment validation.

Such a combination can take place if the PCE is given: (a) the impairment-free WSON network information as discussed in [WSON-Frame] and (b) impairment information to validate potential paths.

3.2.2. Separate Routing, WA, or IV

Separating the processes of routing, WA and/or IV can reduce the need for sharing of different types of information used in path computation. This was discussed for routing separate from WA in [WSON-Frame]. In addition, as will be discussed in the section on network contexts some impairment information may not be shared and this may lead to the need to separate IV from RWA. In addition, as also discussed in the section on network contexts, if IV needs to be done at a high level of precision it may be advantageous to offload this computation to a specialized server.

The following conceptual architectures belong in this general category:

- o R+WA+IV -- separate routing, wavelength assignment, and impairment validation.

- o R + (WA & IV) -- routing separate from a combined wavelength assignment and impairment validation process. Note that impairment validation is typically wavelength dependent hence combining WA with IV can lead to efficiencies.

- o (RWA)+IV - combined routing and wavelength assignment with a separate impairment validation process.

Note that the IV process may come before or after the RWA processes. If RWA comes first then IV is just rendering a yes/no decision on the selected path and wavelength. If IV comes first it would need to

furnish a list of possible (valid with respect to impairments) routes and wavelengths to the RWA processes.

3.2.3. Distributed WA and/or IV

In the non-impairment RWA situation [WSON-Frame] it was shown that a distributed wavelength assignment (WA) process carried out via signaling can eliminate the need to distribute wavelength availability information via an IGP. A similar approach can allow for the distributed computation of impairment effects and avoid the need to distribute impairment characteristics of network elements and links via route protocols or by other means. An example of such an approach is given in [Martinelli] and utilizes enhancements to RSVP signaling to carry accumulated impairment related information.

A distributed impairment validation for a prescribed network path requires that the effects of impairments can be calculated by approximate models with cumulative quality measures such as those in [G.680].

For such a system to be interoperable the various impairment measures to be accumulated would need to be agreed upon. Section 9 of [G.680] can be useful in deriving such cumulative measures but doesn't explicitly state how a distributed computation would take place. For example in the computation of the optical signal to noise ratio along a path (see equation 9-3 of [G.680]) one could accumulate the linear sum terms and convert to the optical signal to noise ratio (OSNR) in (dBs) at the destination or one could convert in and out of the OSNR in (dBs) at each intermediate point along the path.

If distributed WA is being done at the same time as distributed IV then we may need to accumulate impairment related information for all wavelengths that could be used. This is somewhat winnowed down as potential wavelengths are discovered to be in use, but could be a significant burden for lightly loaded high channel count networks.

3.3. Mapping Network Requirements to Architectures

In Figure 1 we show process flows for three main architectural alternatives to IA-RWA when approximate impairment validation suffices. In Figure 2 we show process flows for two main architectural alternatives when detailed impairment verification is required.

```
                  +-------------------------------------+
                  |   +--+     +--------+     +--+      |
                  |   |IV|     |Routing|     |WA|      |
                  |   +--+     +--------+     +--+      |
                  |                                     |
                  |        Combined Processes           |
                  +-------------------------------------+
                                (a)

         +---------------+      +-----------------------+
         | +-----------+ |      | +--------+    +--+    |
         | |    IV     | |      | |Routing|    |WA|    |
         | |candidates| |----->| +--------+    +--+    |
         | +-----------+ |      |  Combined Processes   |
         +---------------+      +-----------------------+
                                (b)

          +------------+        +-----------------------+
          | +--------+ |        |    +--+    +--+       |
          | |Routing| |------->|    |WA|    |IV|       |
          | +--------+ |        |    +--+    +--+       |
          +------------+        | Distributed Processes|
                                +-----------------------+
                                (c)
```

Figure 1 Process flows for the three main approximate impairment architectural alternatives.

The advantages, requirements and suitability of these options are as follows:

o Combined IV & RWA process

This alternative combines RWA and IV within a single computation entity enabling highest potential optimality and efficiency in IA-RWA. This alternative requires that the computational entity knows impairment information as well as non-impairment RWA information. This alternative can be used with "black links", but would then need to be provided by the vendor controlling the "black links".

o IV-Candidates + RWA process

This alternative allows separation of impairment information into two computational entities while still maintaining a high degree of potential optimality and efficiency in IA-RWA. The candidates IV process needs to know impairment information from all optical network elements, while the RWA process needs to know non-impairment RWA

information from the network elements. This alternative can be used with "black links", but the vendor in control of the "black links" would need to provide the functionality of the IV-candidates process. Note that this is still very useful since the algorithmic areas of IV and RWA are very different and prone to specialization.

o Routing + Distributed WA and IV

In this alternative a signaling protocol is extended and leveraged in the wavelength assignment and impairment validation processes. Although this doesn't enable as high a potential degree of optimality of optimality as (a) or (b), it does not require distribution of either link wavelength usage or link/node impairment information. Note that this is most likely not suitable for "black links".

```
       +------------------------------------+     +------------+
       | +-----------+  +--------+    +--+  |     | +--------+ |
       | |    IV     |  |Routing|    |WA|  |     | |  IV    | |
       | |approximate|  +--------+    +--+  |---->| |Detailed| |
       | +-----------+                      |     | +--------+ |
       |        Combined Processes          |     |            |
       +------------------------------------+     +------------+
                                (a)

 +--------------+      +----------------------+     +------------+
 | +----------+ |      | +--------+    +--+    |     | +--------+ |
 | |    IV    | |      | |Routing|    |WA|    |---->| |  IV    | |
 | |candidates| |----->| +--------+    +--+    |     | |Detailed| |
 | +----------+ |      |  Combined Processes  |     | +--------+ |
 +--------------+      +----------------------+     |            |
                                (b)                  +------------+
```

Figure 2 Process flows for the two main detailed impairment validation architectural options.

The advantages, requirements and suitability of these detailed validation options are as follows:

o Combined approximate IV & RWA + Detailed-IV

This alternative combines RWA and approximate IV within a single computation entity enabling highest potential optimality and efficiency in IA-RWA; then has a separate entity performing detailed impairment validation. In the case of "black links" the vendor controlling the "black links" would need to provide all functionality.

o Candidates-IV + RWA + Detailed-IV

This alternative allows separation of approximate impairment information into a computational entity while still maintaining a high degree of potential optimality and efficiency in IA-RWA; then a separate computation entity performs detailed impairment validation. Note that detailed impairment estimation is not standardized.

4. Protocol Implications

The previous IA-RWA architectural alternatives and process flows make differing demands on a GMPLS/PCE based control plane. In this section we discuss the use of (a) an impairment information model, (b) PCE as computational entity assuming the various process roles and consequences for PCEP, (c)any needed extensions to signaling, and (d) extensions to routing. The impacts to the control plane for IA-RWA are summarized in Figure 3.

IA-RWA Option	PCE	Sig	Info Model	Routing
Combined IV & RWA	Yes	No	Yes	Yes
IV-Candidates + RWA	Yes	No	Yes	Yes
Routing + Distributed IV, RWA	No	Yes	Yes	No
Detailed IV	Yes	No	Yes	Yes

Figure 3 IA-RWA architectural options and control plane impacts.

4.1. Information Model for Impairments

As previously discussed all IA-RWA scenarios to a greater or lesser extent rely on a common impairment information model. A number of ITU-T recommendations cover detailed as well as approximate impairment characteristics of fibers and a variety of devices and subsystems. A well integrated impairment model for optical network elements is given in [G.680] and is used to form the basis for an optical impairment model in a companion document [Imp-Info].

It should be noted that the current version of [G.680] is limited to the networks composed of a single WDM line system vendor combined with OADMs and/or PXCs from potentially multiple other vendors, this is known as situation 1 and is shown in Figure 1-1 of [G.680]. It is planed in the future that [G.680] will include networks incorporating line systems from multiple vendors as well as OADMs and/or PXCs from potentially multiple other vendors, this is known as situation 2 and is shown in Figure 1-2 of [G.680].

The case of distributed impairment validation actually requires a bit more than an impairment information model. In particular, it needs a common impairment "computation" model. In the distributed IV case one needs to standardize the accumulated impairment measures that will be conveyed and updated at each node. Section 9 of [G.680] provides guidance in this area with specific formulas given for OSNR, residual dispersion, polarization mode dispersion/polarization dependent loss, effects of channel uniformity, etc... However, specifics of what intermediate results are kept and in what form would need to be standardized.

4.1.1. Properties of an Impairment Information Model

In term of information model there are a set of property that needs to be defined for each optical parameters that need to be in some way considered within an impairment aware control plane.

The properties will help to determine how the control plane can deal with it depending also on the above control plane architectural options. In some case properties value will help to indentify the level of approximation supported by the IV process.

- Time Dependency. This will identify how the impairment may vary along the time. There could be cases where there's no time dependency, while in other cases there is need of an impairment re-evaluation after a certain time. In some cases a level of approximation will consider an impairment that has time dependency as constant.

- Wavelength Dependency. This property will identify if an impairment value can be considered as constant over all the wavelength spectrum of interest or if it has different values. Also in this case a detailed impairment evaluation might lead to consider the exact value while an approximation IV might take a constant value for all wavelengths.

- o Linearity. As impairments are representation of physical effects there are some that have a linear behavior while other are non linear. Linear impairments are in general easy to consider while a non linear will require the knowledge of the full path to be evaluated. An approximation level could only consider linear effects or approximate non-linear impairments in linear ones.

- o Multi-Channel. There are cases where an impairments take different values depending on the aside wavelengths already in place. In this case a dependency among different LSP is introduced. An approximation level can neglect or not the effects on neighbor LSPs.

- o Value range. An impairment that has to be considered by a computational element will needs a representation in bits. So depending on the impairments different types can be considered form integer to real numbers as well as a fixed set of values. This information is important in term of protocol definition and level of approximation introduced by the number representation.

4.2. Routing

Different approaches to path/wavelength impairment validation gives rise to different demands placed on GMPLS routing protocols. In the case where approximate impairment information is used to validate paths GMPLS routing may be used to distribute the impairment characteristics of the network elements and links based on the impairment information model previously discussed. In the case of distributed-IV no new demands would be placed on the routing protocol.

4.3. Signaling

The largest impacts on signaling occur in the cases where distributed impairment validation is performed. In this we need to accumulate impairment information as previously discussed. In addition, since the characteristics of the signal itself, such as modulation type, can play a major role in the tolerance of impairments, this type of information will need to be implicitly or explicitly signaled so that an impairment validation decision can be made at the destination node.

It remains for further study if it may be beneficial to include additional information to a connection request such as desired egress

signal quality (defined in some appropriate sense) in non-distributed IV scenarios.

4.4. PCE

In section 3.3. we gave a number of computation architectural alternatives that could be used to meet the various requirements and constraints of section 3.1. Here we look at how these alternatives could be implemented via either a single PCE or a set of two or more cooperating PCEs, and the impacts on the PCEP protocol.

4.4.1. Combined IV & RWA

In this situation, shown in Figure 1(a), a single PCE performs all the computations needed for IA-RWA.

- TE Database Requirements

  WSON Topology and switching capabilities, WSON WDM link wavelength utilization, and WSON impairment information

- PCC to PCE Request Information

  Signal characteristics/type, required quality, source node, destination node

- PCE to PCC Reply Information

  If the computations completed successfully then the PCE returns the path and its assigned wavelength. If the computations could not complete successfully it would be potentially useful to know the reason why. At a very crude level we'd like to know if this was due to lack of wavelength availability or impairment considerations or a bit of both. The information to be conveyed is for further study.

4.4.2. IV-Candidates + RWA

In this situation, shown in Figure 1(b), we have two separate processes involved in the IA-RWA computation. This requires at least two cooperating PCEs: one for the Candidates-IV process and another for the RWA process. In addition, the overall process needs to be coordinated. This could be done with yet another PCE or we can add this functionality to one of previously defined PCEs. We choose this later option and require the RWA PCE to also act as the overall process coordinator. The roles, responsibilities and information requirements for these two PCEs are given below.

RWA and Coordinator PCE (RWA-Coord-PCE):

Responsible for interacting with PCC and for utilizing Candidates-PCE as needed during RWA computations. In particular it needs to know to use the Candidates-PCE to obtain potential set of routes and wavelengths.

- TE Database Requirements

  WSON Topology and switching capabilities and WSON WDM link wavelength utilization (no impairment information).

- PCC to RWA-PCE request: same as in the combined case.

- RWA-PCE to PCC reply: same as in the combined case.

- RWA-PCE to IV-Candidates-PCE request

  The RWA-PCE asks for a set of at most K routes along with acceptable wavelengths between nodes specified in the original PCC request.

- IV-Candidates-PCE reply to RWA-PCE

  The Candidates-PCE returns a set of at most K routes along with acceptable wavelengths between nodes specified in the RWA-PCE request.

IV-Candidates-PCE:

The IV-Candidates-PCE is responsible for impairment aware path computation. It needs not take into account current link wavelength utilization, but this is not prohibited. The Candidates-PCE is only required to interact with the RWA-PCE as indicated above and not the PCC.

- TE Database Requirements

  WSON Topology and switching capabilities and WSON impairment information (no information link wavelength utilization required).

In Figure 4 we show a sequence diagram for the interactions between the PCC, RWA-PCE and IV-Candidates-PCE.

```
     +---+                +-------------+          +-----------------+
     |PCC|                |RWA-Coord-PCE|          |IV-Candidates-PCE|
     +-+-+                +------+------+          +---------+-------+
       ...___     (a)            |                           |
       |     ````---...____      |                           |
       |                   ```-->|                           |
       |                         |                           |
       |                         |--..___    (b)             |
       |                         |       ```---...___        |
       |                         |                   ```---->|
       |                         |                           |
       |                         |                           |
       |                         |           (c)       ___...|
       |                         |       ___....---''''      |
       |                         |<--''''                    |
       |                         |                           |
       |                         |                           |
       |          (d)      ___...|                           |
       |      ___....---'''      |                           |
       |<--'''                   |                           |
       |                         |                           |
       |                         |                           |
```

Figure 4 Sequence diagram for the interactions between PCC, RWA-Coordinating-PCE and the IV-Candidates-PCE.

In step (a) the PCC requests a path meeting specified quality constraints between two nodes (A and Z) for a given signal represented either by a specific type or a general class with associated parameters. In step (b) the RWA-Coordinating-PCE requests up to K candidate paths between nodes A and Z and associated acceptable wavelengths. In step (c) The IV-Candidates-PCE returns this list to the RWA-Coordinating PCE which then uses this set of paths and wavelengths as input (e.g. a constraint) to its RWA computation. In step (d) the RWA-Coordinating-PCE returns the overall IA-RWA computation results to the PCC.

4.4.3. Approximate IA-RWA + Separate Detailed IV

In Figure 2 we showed two cases where a separate detailed impairment validation process could be utilized. We can place the detailed validation process into a separate PCE. Assuming that a different PCE assumes a coordinating role and interacts with the PCC we can keep the interactions with this separate IV-Detailed-PCE very simple.

IV-Detailed-PCE:

- o TE Database Requirements

  The IV-Detailed-PCE will need optical impairment information, WSON topology, and possibly WDM link wavelength usage information. This document puts no restrictions on the type of information that may be used in these computations.

- o Coordinating-PCE to IV-Detailed-PCE request

  The coordinating-PCE will furnish signal characteristics, quality requirements, path and wavelength to the IV-Detailed-PCE.

- o IV-Detailed-PCE to Coordinating-PCE reply

  The reply is essential an yes/no decision as to whether the requirements could actually be met. In the case where the impairment validation fails it would be helpful to convey information related to cause or quantify the failure, e.g., so a judgment can be made whether to try a different signal or adjust signal parameters.

In Figure 5 we show a sequence diagram for the interactions for the process shown in Figure 2(b). This involves interactions between the PCC, RWA-PCE (acting as coordinator), IV-Candidates-PCE and the IV-Detailed-PCE.

In step (a) the PCC requests a path meeting specified quality constraints between two nodes (A and Z) for a given signal represented either by a specific type or a general class with associated parameters. In step (b) the RWA-Coordinating-PCE requests up to K candidate paths between nodes A and Z and associated acceptable wavelengths. In step (c) The IV-Candidates-PCE returns this list to the RWA-Coordinating PCE which then uses this set of paths and wavelengths as input (e.g. a constraint) to its RWA computation. In step (d) the RWA-Coordinating-PCE request a detailed verification of the path and wavelength that it has computed. In step (e) the IV-Detailed-PCE returns the results of the validation to the RWA-Coordinating-PCE. Finally in step (f)IA-RWA-Coordinating PCE returns the final results (either a path and wavelength or cause for the failure to compute a path and wavelength) to the PCC.

```
                +----------+      +--------------+      +------------+
    +---+       |RWA-Coord |      |IV-Candidates |      |IV-Detailed |
    |PCC|       |   PCE    |      |     PCE      |      |    PCE     |
    +-+-+       +----+-----+      +------+-------+      +-----+------+
      |.._   (a)     |                   |                    |
      |   ``--.__    |                   |                    |
      |          `-->|                   |                    |
      |              |        (b)        |                    |
      |              |--....____         |                    |
      |              |          ````---.>|                    |
      |              |                   |                    |
      |              |         (c)  __..-|                    |
      |              |     __..---''     |                    |
      |              |<--''              |                    |
      |              |                                        |
      |              |...._____          (d)                  |
      |              |         `````-----....._____           |
      |              |                             `````----->|
      |              |                                        |
      |              |                 (e)          _____.....+
      |              |          _____.....-----'''''          |
      |              |<----'''''                              |
      |     (f)   __.|                                        |
      |    __.--''   |
      |<-''          |
      |              |
```

Figure 5 Sequence diagram for the interactions between PCC, RWA-Coordinating-PCE, IV-Candidates-PCE and IV-Detailed-PCE.

5. Security Considerations

This document discusses a number of control plane architectures that incorporate knowledge of impairments in optical networks. If such architecture is put into use within a network it will by its nature contain details of the physical characteristics of an optical network. Such information would need to be protected from intentional or unintentional disclosure.

6. IANA Considerations

This draft does not currently require any consideration from IANA.

7. Acknowledgments

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APPENDIX A: Overview of Optical Layer ITU-T Recommendations

For optical fiber, devices, subsystems and network elements the ITU-T has a variety of recommendations that include definitions, characterization parameters and test methods. In the following we take a bottom up survey to emphasize the breadth and depth of the existing recommendations. We focus on digital communications over single mode optical fiber.

A.1. Fiber and Cables

Fibers and cables form a key component of what from the control plane perspective could be termed an optical link. Due to the wide range of uses of optical networks a fairly wide range of fiber types are used in practice. The ITU-T has three main recommendations covering the definition of attributes and test methods for single mode fiber:

o Definitions and test methods for linear, deterministic attributes of single-mode fibre and cable [G.650.1]

o Definitions and test methods for statistical and non-linear related attributes of single-mode fibre and cable [G.650.2]

o Test methods for installed single-mode fibre cable sections [G.650.3]

General Definitions[G.650.1]: Mechanical Characteristics (numerous), Mode field characteristics(mode field, mode field diameter, mode field centre, mode field concentricity error, mode field non-circularity), Glass geometry characteristics, Chromatic dispersion definitions (chromatic dispersion, group delay, chromatic dispersion coefficient, chromatic dispersion slope, zero-dispersion wavelength, zero-dispersion slope), cut-off wavelength, attenuation. Definition of equations and fitting coefficients for chromatic dispersion (Annex A). [G.650.2] polarization mode dispersion (PMD) - phenomenon of PMD, principal states of polarization (PSP), differential group delay (DGD), PMD value, PMD coefficient, random mode coupling, negligible mode coupling, mathematical definitions in terms of Stokes or Jones vectors. Nonlinear attributes: Effective area, correction factor k, non-linear coefficient (refractive index dependent on intensity), Stimulated Billouin scattering.

Tests defined [G.650.1]: Mode field diameter, cladding diameter, core concentricity error, cut-off wavelength, attenuation, chromatic dispersion. [G.650.2]: test methods for polarization mode dispersion. [G.650.3] Test methods for characteristics of fibre cable sections following installation: attenuation, splice loss, splice location,

fibre uniformity and length of cable sections (these are OTDR based), PMD, Chromatic dispersion.

With these definitions a variety of single mode fiber types are defined as shown in the table below:

ITU-T Standard	Common Name
G.652 [G.652]	Standard SMF
G.653 [G.653]	Dispersion shifted SMF
G.654 [G.654]	Cut-off shifted SMF
G.655 [G.655]	Non-zero dispersion shifted SMF
G.656 [G.656]	Wideband non-zero dispersion shifted SMF

A.2. Devices

A.2.1. Optical Amplifiers

Optical amplifiers greatly extend the transmission distance of optical signals in both single channel and multi channel (WDM) subsystems. The ITU-T has the following recommendations:

- Definition and test methods for the relevant generic parameters of optical amplifier devices and subsystems [G.661]

- Generic characteristics of optical amplifier devices and subsystems [G.662]

- Application related aspects of optical amplifier devices and subsystems [G.663]

- Generic characteristics of Raman amplifiers and Raman amplified subsystems [G.665]

Reference [G.661] starts with general classifications of optical amplifiers based on technology and usage, and include a near exhaustive list of over 60 definitions for optical amplifier device attributes and parameters. In references [G.662] and [G.665] we have characterization of specific devices, e.g., semiconductor optical amplifier, used in a particular setting, e.g., line amplifier. For example reference[G.662] gives the following minimum list of relevant parameters for the specification of an optical amplifier device used as line amplifier in a multichannel application:

a) Channel allocation.

b) Total input power range.

c) Channel input power range.

d) Channel output power range.

e) Channel signal-spontaneous noise figure.

f) Input reflectance.

g) Output reflectance.

h) Maximum reflectance tolerable at input.

i) Maximum reflectance tolerable at output.

j) Maximum total output power.

k) Channel addition/removal (steady-state) gain response.

l) Channel addition/removal (transient) gain response.

m) Channel gain.

n) Multichannel gain variation (inter-channel gain difference).

o) Multichannel gain-change difference (inter-channel gain-change difference).

p) Multichannel gain tilt (inter-channel gain-change ratio).

q) Polarization Mode Dispersion (PMD).

A.2.2. Dispersion Compensation

In optical systems two forms of dispersion are commonly encountered [RFC4054] chromatic dispersion and polarization mode dispersion (PMD). There are a number of techniques and devices used for compensating for these effects. The following ITU-T recommendations characterize such devices:

o Characteristics of PMD compensators and PMD compensating receivers [G.666] o Characteristics of Adaptive Chromatic Dispersion Compensators [G.667]

The above furnish definitions as well as parameters and characteristics. For example in [G.667] adaptive chromatic dispersion compensators are classified as being receiver, transmitter or line based, while in [G.666] PMD compensators are only defined for line and receiver configurations. Parameters that are common to both PMD and chromatic dispersion compensators include: line fiber type, maximum and minimum input power, maximum and minimum bit rate, and modulation type. In addition there are a great many parameters that apply to each type of device and configuration.

A.2.3. Optical Transmitters

The definitions of the characteristics of optical transmitters can be found in references [G.957], [G.691], [G.692] and [G.959.1]. In addition references [G.957], [G.691], and [G.959.1] define specific parameter values or parameter ranges for these characteristics for interfaces for use in particular situations.

We generally have the following types of parameters

Wavelength related: Central frequency, Channel spacing, Central frequency deviation[G.692].

Spectral characteristics of the transmitter: Nominal source type (LED, MLM lasers, SLM lasers) [G.957], Maximum spectral width, Chirp parameter, Side mode suppression ratio, Maximum spectral power density [G.691].

Power related: Mean launched power, Extinction ration, Eye pattern mask [G.691], Maximum and minimum mean channel output power [G.959.1].

A.2.4. Optical Receivers

References [G.959.1], [G.691], [G.692] and [G.957], define optical receiver characteristics and [G.959.1], [G.691] and [G.957]give specific values of these parameters for particular interface types and network contexts.

The receiver parameters include:

Receiver sensitivity: minimum value of average received power to achieve a 1x10-10 BER [G.957] or 1x10-12 BER [G.691]. See [G.957] and [G.691] for assumptions on signal condition.

Receiver overload: Receiver overload is the maximum acceptable value of the received average power for a 1x10.10 BER [G.957] or a 1x10-12 BER [G.691].

Receiver reflectance: "Reflections from the receiver back to the cable plant are specified by the maximum permissible reflectance of the receiver measured at reference point R."

Optical path power penalty: "The receiver is required to tolerate an optical path penalty not exceeding X dB to account for total degradations due to reflections, intersymbol interference, mode partition noise, and laser chirp."

When dealing with multi-channel systems or systems with optical amplifiers we may also need:

Optical signal-to-noise ratio: "The minimum value of optical SNR required to obtain a 1x10-12 BER."[G.692]

Receiver wavelength range: "The receiver wavelength range is defined as the acceptable range of wavelengths at point Rn. This range must be wide enough to cover the entire range of central frequencies over the OA passband." [G.692]

Minimum equivalent sensitivity: "This is the minimum sensitivity that would be required of a receiver placed at MPI-RM in multichannel applications to achieve the specified maximum BER of the application code if all except one of the channels were to be removed (with an ideal loss-less filter) at point MPI-RM." [G.959.1]

A.3. Components and Subsystems

Reference [G.671] "Transmission characteristics of optical components and subsystems" covers the following components:

- optical add drop multiplexer (OADM) subsystem;
- asymmetric branching component;
- optical attenuator;
- optical branching component (wavelength non-selective);
- optical connector;
- dynamic channel equalizer (DCE);

- optical filter;
- optical isolator;
- passive dispersion compensator;
- optical splice;
- optical switch;
- optical termination;
- tuneable filter;
- optical wavelength multiplexer (MUX)/demultiplexer (DMUX);
    - coarse WDM device;
    - dense WDM device;
    - wide WDM device.

Reference [G.671] then specifies applicable parameters for these components. For example an OADM subsystem will have parameters such as: insertion loss (input to output, input to drop, add to output), number of add, drop and through channels, polarization dependent loss, adjacent channel isolation, allowable input power, polarization mode dispersion, etc...

A.4. Network Elements

The previously cited ITU-T recommendations provide a plethora of definitions and characterizations of optical fiber, devices, components and subsystems. Reference [G.Sup39] "Optical system design and engineering considerations" provides useful guidance on the use of such parameters.

In many situations the previous models while good don't encompass the higher level network structures that one typically deals with in the control plane, i.e, "links" and "nodes". In addition such models include the full range of network applications from planning, installation, and possibly day to day network operations, while with the control plane we are generally concerned with a subset of the later. In particular for many control plane applications we are interested in formulating the total degradation to an optical signal as it travels through multiple optical subsystems, devices and fiber segments.

In reference [G.680] "Physical transfer functions of optical networks elements", a degradation function is currently defined for the following optical network elements: (a) DWDM Line segment, (b) Optical Add/Drop Multiplexers (OADM), and (c) Photonic cross-connect (PXC). The scope of [G.680] is currently for optical networks consisting of one vendors DWDM line systems along with another vendors OADMs or PXCs.

The DWDM line system of [G.680] consists of the optical fiber, line amplifiers and any embedded dispersion compensators. Similarly the OADM/PXC network element may consist of the basic OADM component and optionally included optical amplifiers. The parameters for these optical network elements (ONE) are given under the following circumstances:

o General ONE without optical amplifiers

o General ONE with optical amplifiers

o OADM without optical amplifiers

o OADM with optical amplifiers

o Reconfigurable OADM (ROADM) without optical amplifiers

o ROADM with optical amplifiers

o PXC without optical amplifiers

o PXC with optical amplifiers

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