Internet Engineering Task Force (IETF)
Request for Comments: 6566
Category: Informational
ISSN: 2070-1721

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March 2012

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

Abstract

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, these processes are usually referred to as "impairments". These physical characteristics may be important constraints to consider when using a GMPLS control plane to support path setup and maintenance in wavelength switched optical networks.

This document provides a framework for applying GMPLS protocols and the Path Computation Element (PCE) architecture to support Impairment-Aware Routing and Wavelength Assignment (IA-RWA) in wavelength switched optical networks. Specifically, this document discusses key computing constraints, scenarios, and architectural processes: routing, wavelength assignment, and impairment validation. This document does not define optical data plane aspects; impairment parameters; or measurement of, or assessment and qualification of, a route; rather, it describes the architectural and information components for protocol solutions.

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Table of Contents

1. Introduction 3
2. Terminology 4
3. Applicability 6
4. Impairment-Aware Optical Path Computation 7
   4.1. Optical Network Requirements and Constraints 8
        4.1.1. Impairment-Aware Computation Scenarios 9
        4.1.2. Impairment Computation and Information-Sharing Constraints 10
        4.1.3. Impairment Estimation Process 11
   4.2. IA-RWA Computation and Control Plane Architectures 13
        4.2.1. Combined Routing, WA, and IV 15
        4.2.2. Separate Routing, WA, or IV 15
        4.2.3. Distributed WA and/or IV 16
   4.3. Mapping Network Requirements to Architectures 16
5. Protocol Implications 19
   5.1. Information Model for Impairments 19
   5.2. Routing 20
   5.3. Signaling 21
   5.4. PCE 21
        5.4.1. Combined IV & RWA 21
        5.4.2. IV-Candidates + RWA 22
        5.4.3. Approximate IA-RWA + Separate Detailed-IV 24
6. Manageability and Operations 25
7. Security Considerations 26
8. References 27
   8.1. Normative References 27
   8.2. Informative References 27
9. Contributors 29

1. Introduction

Wavelength Switched Optical Networks (WSONs) are constructed from subsystems that may include wavelength division multiplexed links, tunable transmitters and receivers, Reconfigurable Optical Add/Drop Multiplexers (ROADMs), wavelength converters, and electro-optical network elements. A WSON is a Wavelength Division Multiplexing (WDM)-based optical network in which switching is performed selectively based on the center wavelength of an optical signal.

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, these processes are usually referred to as "impairments". Optical impairments accumulate along the path (without 3R regeneration [G.680]) 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.

In order to provision an optical connection (an optical path) through a WSON, a combination of path continuity, resource availability, and impairment constraints must be met to determine viable and optimal paths through the network. The determination of appropriate paths is known as Impairment-Aware Routing and Wavelength Assignment (IA-RWA).

Generalized Multi-Protocol Label Switching (GMPLS) [RFC3945] provides a set of control plane protocols that can be used to operate networks ranging from packet switch capable networks to those networks that use time division multiplexing and WDM. The Path Computation Element (PCE) architecture [RFC4655] defines functional computation components that can be used in cooperation with the GMPLS control plane to compute and suggest appropriate paths. [RFC4054] provides an overview of optical impairments and their routing (path selection) implications for GMPLS. This document uses [G.680] and other ITU-T Recommendations as references for the optical data plane aspects.

This document provides a framework for applying GMPLS protocols and the PCE architecture to the control and operation of IA-RWA for WSONs. To aid in this evaluation, this document provides an overview of the subsystems and processes that comprise WSONs and describes IA-RWA models based on the corresponding ITU-T Recommendations, so that the information requirements for use by GMPLS and PCE systems can be identified. This work will facilitate the development of protocol extensions in support of IA-RWA within the GMPLS and PCE protocol families.

2. Terminology

ADM: Add/Drop Multiplexer. An optical device used in WDM networks and composed of one or more line side ports and, typically, many tributary ports.

Black Links: Black links refer to tributary interfaces where only link characteristics are defined. This approach enables transverse compatibility at the single-channel point using a direct wavelength-multiplexing configuration.

CWDM: Coarse Wavelength Division Multiplexing

DGD: Differential Group Delay

DWDM: Dense Wavelength Division Multiplexing

FOADM: Fixed Optical Add/Drop Multiplexer

GMPLS: Generalized Multi-Protocol Label Switching

IA-RWA: Impairment-Aware Routing and Wavelength Assignment

Line Side: In a WDM system, line side ports and links typically can carry the full multiplex of wavelength signals, as compared to tributary (add or drop ports), which typically carry a few (typically one) wavelength signals.

NEs: Network Elements

OADMs: Optical Add/Drop Multiplexers

OSNR: Optical Signal-to-Noise Ratio

OXC: Optical Cross-Connect. An optical switching element in which a signal on any input port can reach any output port.

PCC: Path Computation Client. Any client application requesting that a path computation be performed by the Path Computation Element.

PCE: Path Computation Element. An entity (component, application, or network node) that is capable of computing a network path or route based on a network graph and application of computational constraints.

PCEP: PCE Communication Protocol. The communication protocol between a Path Computation Client and Path Computation Element.

PXC: Photonic Cross-Connect

Q-Factor: The Q-factor provides a qualitative description of the receiver performance. It is a function of the optical signal-to-noise ratio. The Q-factor suggests the minimum SNR (Signal-to-Noise Ratio) required to obtain a specific bit error rate (BER) for a given signal.

ROADM: Reconfigurable Optical Add/Drop Multiplexer. A wavelength-selective switching element featuring input and output line side ports as well as add/drop tributary ports.

RWA: Routing and Wavelength Assignment

Transparent Network: A Wavelength Switched Optical Network that does not contain regenerators or wavelength converters.

Translucent Network: A Wavelength Switched Optical Network that is predominantly transparent but may also contain limited numbers of regenerators and/or wavelength converters.

Tributary: A link or port on a WDM system that can carry significantly less than the full multiplex of wavelength signals found on the line side links/ports. Typical tributary ports are the add and drop ports on an ADM, and these support only a single wavelength channel.

Wavelength Conversion/Converters: The process of converting an information-bearing optical signal centered at a given wavelength to information with "equivalent" content centered at a different wavelength. Wavelength conversion can be implemented via an optical-electronic-optical (OEO) process or via a strictly optical process.

WDM: Wavelength Division Multiplexing

Wavelength Switched Optical Networks (WSONs): WDM-based optical networks in which switching is performed selectively based on the center wavelength of an optical signal.

3. Applicability

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

- WSONs are evolving and are using multi-degree optical cross-connects in such a way that network topologies are changing from rings (and interconnected rings) to general mesh. Adding network equipment such as amplifiers or regenerators to ensure that all paths are 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’s life; e.g., the optical interfaces might be upgraded to higher bitrates. Such changes could result in paths being unsuitable for the optical signal. Moreover, the optical physical interfaces 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.

- With the recent bitrate increases from 10G to 40G and 100G over a single wavelength, WSONs will likely be operated with a mix of wavelengths at different bitrates. This operational scenario will impose impairment constraints due to different physical behavior of different bitrates and associated modulation formats.

Not having an impairment-aware control plane for such networks will require a more complex network design phase that needs to take into account the evolving network status in terms of equipment and traffic at the beginning stage. In addition, network operations such as path establishment will require significant pre-design via non-control-plane processes, resulting in significantly slower network provisioning.

It should be highlighted that the impact of impairments and use in determination of path viability is not sufficiently well established for general applicability [G.680]; it will depend on network implementations. The use of an impairment-aware control plane, and the set of information distributed, will need to be evaluated on a case-by-case scenario.

4. Impairment-Aware Optical Path Computation

The basic criterion 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 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.

Impairment-aware path calculation also needs to take into account when regeneration is used along the path. [RFC6163] provides background on the concept of optical translucent networks that contain transparent elements and electro-optical elements such as OEO regenerations. In such networks, a generic light path can go through a number of regeneration points.

Regeneration points could happen for two reasons:

(i) Wavelength conversion is performed in order to assist RWA in avoiding wavelength blocking. This is the impairment-free case covered by [RFC6163].

(ii) The optical signal without regeneration would be too degraded to meet end-to-end BER requirements. This is the case when RWA takes into consideration impairment estimation covered by this document.

In the latter case, an optical path can be seen as a set of transparent segments. The calculation of optical impairments needs to be reset at each regeneration point so each transparent segment will have its own impairment evaluation.

```
+---+    +----+   +----+     +-----+     +----+    +---+
| I |----| N1 |---| N2 |-----| REG |-----| N3 |----| E |
+---+    +----+   +----+     +-----+     +----+    +---+

|<---------------------------->|<-------------------->|
           Segment 1                    Segment 2
```

Figure 1. Optical Path as a Set of Transparent Segments

For example, Figure 1 represents an optical path from node I to node E with a regeneration point, REG, in between. This is feasible from an impairment validation perspective if both segments (I, N1, N2, REG) and (REG, N3, E) are feasible.

4.1. Optical Network Requirements and Constraints

This section examines the various optical network requirements and constraints under which an impairment-aware optical control plane may have to operate. These requirements and constraints motivate the IA-RWA architectural alternatives presented in Section 4.2. Different optical network contexts can be broken into 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.

4.1.1. Impairment-Aware Computation Scenarios

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; after that -- for example, during optical path computation -- they can be ignored. This is the case discussed in [RFC6163] where impairments may be ignored by the control plane and only optical parameters related to signal compatibility are considered.

C. Approximated Impairment Estimation

This situation is applicable to networks in which impairment effects need to be considered but where there is a sufficient margin such that impairment effects can be estimated via such approximation techniques 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]. This is generally known as the linear case, where only linear effects are taken into account. Note that adding or removing an optical signal on the path should not render any of the existing signals in the network non-viable. For example, one form of non-viability is the occurrence in existing links of transients of sufficient magnitude to impact the BER of existing signals.

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

D. Accurate 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 need to be performed prior to the addition of a new path. Currently, no impairment models are available from ITU-T, and this scenario is outside the scope of this document.

4.1.2. 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. However, note that the overall impact of a black link at the single-channel interface points is limited by [G.698.1] and [G.698.2].

Typically, a vendor might use proprietary impairment models for DWDM spans in order 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 in the path could not be performed by a general-purpose IA computation entity, since it would not have access to or understand the black-link impairment parameters. However, impairment estimation (optical path validation) could be performed by a vendor-specific IA computation entity. Such a vendor-specific IA computation entity could utilize standardized impairment information imported from other network elements in these proprietary computations.

In the following, the term "black links" will be used to describe these computation and information-sharing constraints in optical networks. From the control plane perspective, the following options are considered:

1. The authority in control of the black links can furnish a list of all viable paths between all viable node pairs to a computation entity. This information would be particularly useful as an input to RWA optimization to be performed by another computation entity. The difficulty here is that such a list of paths, along with any wavelength constraints, could get unmanageably large as the size of the network increases.

2. The authority in control of the black links could provide a PCE-like entity 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.

3. The authority in control of the black links provides a PCE that performs full IA-RWA services. The difficulty here is that this option requires the one authority to also become the sole source of all RWA optimization algorithms.

In all of the above cases, it would be the responsibility of the authority 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.

4.1.3. Impairment Estimation Process

The impairment estimation process can be modeled through 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 functions, as detailed in the following sections.

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

Starting from the functional block on the left, the optical interface represents where the optical signal is transmitted or received and defines the properties at the path endpoints. Even the impairment-free case, such as scenario B in Section 4.1.1, needs to consider a minimum set of interface characteristics. In such a case, only a few parameters used to assess the signal compatibility will be taken into account (see [RFC6163]). For the impairment-aware case, these parameters may be sufficient or not, depending on the accepted level of approximation (scenarios C and D). This functional block highlights the need to consider a set of interface parameters during the impairment validation process.

The "Optical Impairment Path" block represents the types of impairments affecting a wavelength as it traverses the networks through links and nodes. In the case of a network where there are no impairments (scenario A), this block will not be present. Otherwise, this function must be implemented in some way via the control plane. Architectural alternatives to accomplish this are provided in Section 4.2. This block implementation (e.g., through routing, signaling, or a PCE) may influence the way the control plane distributes impairment information within the network.

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 the case of no IA approximation, only the signal class compatibility will be verified. In addition to a feasible/not-feasible result, it may be worthwhile for decision functions to consider the case in which paths would likely be feasible within some degree of confidence. The optical impairments are usually not fixed values, as they may vary within ranges of values according to the approach taken in the physical modeling (worst-case, statistical, or based on typical values). For example, the utilization of the worst-case value for each parameter within the impairment validation process may lead to marking some paths as not feasible, while they are very likely to be, in reality, feasible.

4.2. IA-RWA Computation and Control Plane Architectures

From a control plane point of view, optical impairments are additional constraints to the impairment-free RWA process described in [RFC6163]. In IA-RWA, there are conceptually three general classes of processes to be considered: Routing (R), Wavelength Assignment (WA), and Impairment Validation (IV), i.e., estimation.

Impairment validation may come in many forms and may be invoked at different levels of detail in the IA-RWA process. All of the variations of impairment validation discussed in this section are based on scenario C ("Approximated Impairment Estimation") as discussed in Section 4.1.1. From a process point of view, the following three forms of impairment validation will be considered:

- IV-Candidates

  In this case, an 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 actually be available in the network, due to its current usage state. This set of paths could 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. Note also that this case includes any paths between the source and destination that may have been "pre-validated".

  In this case, the control plane simply makes use of candidate paths but does not have any optical impairment information. Another option is when the path validity is assessed within the control plane. The following cases highlight this situation.

- IV-Approximate Verification

  Here, approximation methods are used to estimate the impairments experienced by a signal. Impairments are typically approximated by linear and/or statistical characteristics of individual or combined components and fibers along the signal path.

- 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.

The next two cases refer to the way an impairment validation computation can be performed from a decision-making point of view.

- IV-Centralized

  In this case, impairments to a path are computed at a single entity. The information concerning impairments, however, may still be gathered from network elements. Depending on how information is gathered, this may put additional requirements on routing protocols. This topic will be detailed in later sections.

- IV-Distributed

  In the distributed IV process, approximate degradation measures such as OSNR, dispersion, DGD, etc., may be accumulated along the path via signaling. Each node on the path may already perform some part of the impairment computation (i.e., distributed). 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, but it does not generally require distributing optical parameters to the entire network.

The control plane must not preclude the possibility of concurrently performing one or all of the above cases in the same network. For example, there could be cases where a certain number of paths are already pre-validated (IV-Candidates), so the control plane may set up one of those paths without requesting any impairment validation procedure. On the same network, however, the control plane may compute a path outside the set of IV-Candidates for which an impairment evaluation can be necessary.

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

4.2.1. Combined Routing, WA, and IV

From the point of view of optimality, reasonably good IA-RWA solutions can be achieved if the 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 information as discussed in [RFC6163] and (b) impairment information to validate potential paths.

4.2.2. Separate Routing, WA, or IV

Separating the processes of routing, WA, and/or IV can reduce the need for the sharing of different types of information used in path computation. This was discussed for routing, separate from WA, in [RFC6163]. In addition, as was discussed in Section 4.1.2, some impairment information may not be shared, and this may lead to the need to separate IV from RWA. In addition, 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:

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

- 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 improved efficiency.

- (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.

4.2.3. Distributed WA and/or IV

In the non-impairment RWA situation [RFC6163], it was shown that a distributed WA process carried out via signaling can eliminate the need to distribute wavelength availability information via an interior gateway protocol (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 by routing protocols or by other means. Therefore, the following conceptual options belong to this category:

- RWA + D(IV)
  combined routing and wavelength assignment and distributed impairment validation.

- R + D(WA & IV)
  routing separate from a distributed wavelength assignment and impairment validation process.

Distributed impairment validation for a prescribed network path requires that the effects of impairments be calculated by approximate models with cumulative quality measures such as those given in [G.680]. The protocol encoding of the impairment-related information from [G.680] would need to be agreed upon.

If distributed WA is being done at the same time as distributed IV, then it is necessary to accumulate impairment-related information for all wavelengths that could be used. The amount of information is reduced somewhat as potential wavelengths are discovered to be in use but could be a significant burden for lightly loaded networks with high channel counts.

4.3. Mapping Network Requirements to Architectures

Figure 2 shows process flows for the three main architectural alternatives to IA-RWA that apply when approximate impairment validation is sufficient. Figure 3 shows process flows for the two main architectural alternatives that apply 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 2. Process Flows for the Three Main Approximate Impairment Architectural Alternatives

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

- 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 computation entity have 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 authority controlling the black links.

- IV-Candidates + RWA process

  This alternative allows separation of impairment information into two computation entities while still maintaining a high degree of potential optimality and efficiency in IA-RWA. The IV-Candidates process needs to have impairment information from all optical network elements, while the RWA process needs to have non-impairment RWA information from the network elements. This alternative can be used with black links, but the authority 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 conducive to specialization.

- o Routing + Distributed WA and IV

  In this alternative, a signaling protocol may be extended and leveraged in the wavelength assignment and impairment validation processes. Although this doesn’t enable as high a potential degree 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 3. 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 the highest potential optimality and efficiency in IA-RWA while keeping a separate entity performing detailed impairment validation. In the case of black links, the authority controlling the black links would need to provide all functionality.

- IV-Candidates + RWA + Detailed-IV

  This alternative allows separation of approximate impairment information into a computation 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.

5. Protocol Implications

The previous IA-RWA architectural alternatives and process flows make differing demands on a GMPLS/PCE-based control plane. This section discusses the use of (a) an impairment information model, (b) the PCE as computation entity assuming the various process roles and consequences for PCEP, (c) possible extensions to signaling, and (d) possible extensions to routing. This document is providing this evaluation to aid protocol solutions work. The protocol specifications may deviate from this assessment. The assessment of the impacts to the control plane for IA-RWA is summarized in Figure 4.

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

Figure 4. IA-RWA Architectural Options and Control Plane Impacts

5.1. Information Model for Impairments

As previously discussed, most IA-RWA scenarios rely, to a greater or lesser extent, on a common impairment information model. A number of ITU-T Recommendations cover both detailed and approximate impairment characteristics of fibers, a variety of devices, and a variety of subsystems. An impairment model that can be used as a guideline for optical network elements and assessment of path viability is given in [G.680].

It should be noted that the current version of [G.680] is limited to 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 planned 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].

For the case of distributed IV, this would require more than an impairment information model. It would need 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, and effects of channel uniformity. However, specifics of what intermediate results are kept and in what form would need to be standardized for interoperability. As noted in [G.680], this information may possibly not be sufficient, and in such a case, the applicability would be network dependent.

5.2. Routing

Different approaches to path/wavelength impairment validation give 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.

Depending on the computational alternative, the routing protocol may need to advertise information necessary to the impairment validation process. This can potentially cause scalability issues, due to the high volume of data that need to be advertised. Such issues can be addressed by separating data that need to be advertised only rarely from data that need to be advertised more frequently, or by adopting other forms of awareness solutions as described in previous sections (e.g., a centralized and/or external IV entity).

In terms of scenario C in Section 4.1.1, the model defined by [G.680] will apply, and the routing protocol will need to gather information required for such computations.

In the case of distributed IV, no new demands would be placed on the routing protocol.

5.3. Signaling

The largest impacts on signaling occur in the cases where distributed impairment validation is performed. In this case, it is necessary 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 whether 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.

5.4. PCE

In Section 4.2, a number of computational architectural alternatives were given that could be used to meet the various requirements and constraints of Section 4.1. Here, the focus is on 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. This document provides this evaluation to aid solutions work. The protocol specifications may deviate from this assessment.

5.4.1. Combined IV & RWA

In this situation, shown in Figure 2(a), a single PCE performs all of the computations needed for IA-RWA.

- Traffic Engineering (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, and 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 why. At a minimum, it is of interest to know if this was due to lack of wavelength availability, impairment considerations, or both. The information to be conveyed is for further study.

5.4.2. IV-Candidates + RWA

In this situation, as shown in Figure 2(b), two separate processes are involved in the IA-RWA computation. This requires two cooperating path computation entities: one for the IV-Candidates 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 this functionality could be added to one of a number of previously defined entities. This later option requires that the RWA entity also act as the overall process coordinator. The roles, responsibilities, and information requirements for these two entities, when instantiated as PCEs, are given below.

RWA and Coordinator PCE (RWA-Coord PCE):

The RWA-Coord PCE is responsible for interacting with the PCC and for utilizing the IV-Candidates PCE as needed during RWA computations. In particular, it needs to know that it is to use the IV-Candidates PCE to obtain a potential set of routes and wavelengths.

- o TE Database requirements: WSON topology and switching capabilities, and WSON WDM link wavelength utilization (no impairment information).

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

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

- o 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.

- o IV-Candidates PCE reply to RWA PCE: The IV-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 need not take into account current link wavelength utilization, but this is not prohibited. The IV-Candidates PCE is only required to interact with the RWA PCE as indicated above, and not the initiating PCC. Note: The RWA-Coord PCE is also a PCC with respect to the IV-Candidate.

- TE Database requirements: WSON topology and switching capabilities, and WSON impairment information (no information link wavelength utilization required).

Figure 5 shows a sequence diagram for the possible interactions between the PCC, RWA-Coord PCE, and IV-Candidates PCE.

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

Figure 5. Sequence Diagram for the Interactions between the PCC, RWA-Coord PCE, and IV-Candidates PCE

In step (a), the PCC requests a path that meets 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-Coord PCE requests up to K candidate paths between nodes A and Z, and associated acceptable wavelengths. The term "K candidate paths" is associated with the k shortest path algorithm. It refers to an algorithm that finds multiple k short paths connecting the source and the destination in a graph allowing repeated vertices and edges in the paths. See details in [Eppstein].

In step (c), the IV-Candidates PCE returns this list to the RWA-Coord 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-Coord PCE returns the overall IA-RWA computation results to the PCC.

5.4.3. Approximate IA-RWA + Separate Detailed-IV

Previously, Figure 3 showed two cases where a separate detailed impairment validation process could be utilized. It is possible to place the detailed validation process into a separate PCE. Assuming that a different PCE assumes a coordinating role and interacts with the PCC, it is possible to keep the interactions with this separate IV-Detailed PCE very simple. Note that, from a message flow perspective, there is some inefficiency as a result of separating the IV-Candidates PCE from the IV-Detailed PCE in order to achieve a high degree of potential optimality.

IV-Detailed PCE:

- 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.

- RWA-Coord PCE to IV-Detailed PCE request: The RWA-Coord PCE will furnish signal characteristics, quality requirements, path, and wavelength to the IV-Detailed PCE.

- IV-Detailed PCE to RWA-Coord PCE reply: The reply is essentially a 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 the cause or to quantify the failure, e.g., so that a judgment can be made regarding whether to try a different signal or adjust signal parameters.

Figure 6 shows a sequence diagram for the interactions corresponding to the process shown in Figure 3(b). This involves interactions between the PCC, RWA PCE (acting as coordinator), IV-Candidates PCE, and IV-Detailed PCE.

In step (a), the PCC requests a path that meets 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-Coord 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-Coord 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-Coord PCE requests 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-Coord PCE. Finally, in step (f), the RWA-Coord PCE returns the final results (either a path and wavelength, or a 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 6. Sequence Diagram for the Interactions between the PCC, RWA-Coord PCE, IV-Candidates PCE, and IV-Detailed PCE

6. Manageability and Operations

The issues concerning manageability and operations are beyond the scope of this document. The details of manageability and operational issues will have to be deferred to future protocol implementations.

On a high level, the GMPLS-routing-based architecture discussed in Section 5.2 may have to deal with how to resolve potential scaling issues associated with disseminating a large amount of impairment characteristics of the network elements and links.

From a scaling point of view, the GMPLS-signaling-based architecture discussed in Section 5.3 would be more scalable than other alternatives, as this architecture would avoid the dissemination of a large amount of data to the networks. This benefit may come, however, at the expense of potentially inefficient use of network resources.

The PCE-based architectures discussed in Section 5.4 would have to consider operational complexity when implementing options that require the use of multiple PCE servers. The most serious case is the option discussed in Section 5.4.3 ("Approximate IA-RWA + Separate Detailed-IV"). The combined IV & RWA option (which was discussed in Section 5.4.1), on the other hand, is simpler to operate than are other alternatives, as one PCE server handles all functionality; however, this option may suffer from a heavy computation and processing burden compared to other alternatives.

Interoperability may be a hurdle to overcome when trying to agree on some impairment parameters, especially those that are associated with the black links. This work has been in progress in ITU-T and needs some more time to mature.

7. Security Considerations

This document discusses a number of control plane architectures that incorporate knowledge of impairments in optical networks. If such an 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, similar to other network information used within intra-domain protocols.

This document does not require changes to the security models within GMPLS and associated protocols. That is, the OSPF-TE, RSVP-TE, and PCEP security models could be operated unchanged. However, satisfying the requirements for impairment information dissemination using the existing protocols may significantly affect the loading of those protocols and may make the operation of the network more vulnerable to active attacks such as injections, impersonation, and man-in-the-middle attacks. Therefore, additional care may be required to ensure that the protocols are secure in the impairment-aware WSON environment.

Furthermore, the additional information distributed in order to address impairment information represents a disclosure of network capabilities that an operator may wish to keep private. Consideration should be given to securing this information. For a general discussion on MPLS- and GMPLS-related security issues, see the MPLS/GMPLS security framework [RFC5920] and, in particular, text detailing security issues when the control plane is physically separated from the data plane.

8. References

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