                        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.

Status of This Memo

   This document is not an Internet Standards Track specification; it is
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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:

   o 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.

   o 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.

   o 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.

o 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
```
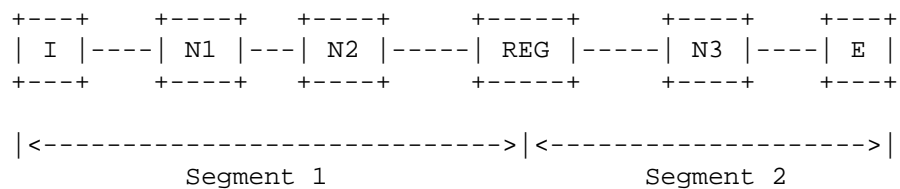
        Figure 1. Optical Path as a Set of Transparent Segments

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 | |
                                       | +-----------+ |
                                       +-----------------+
```
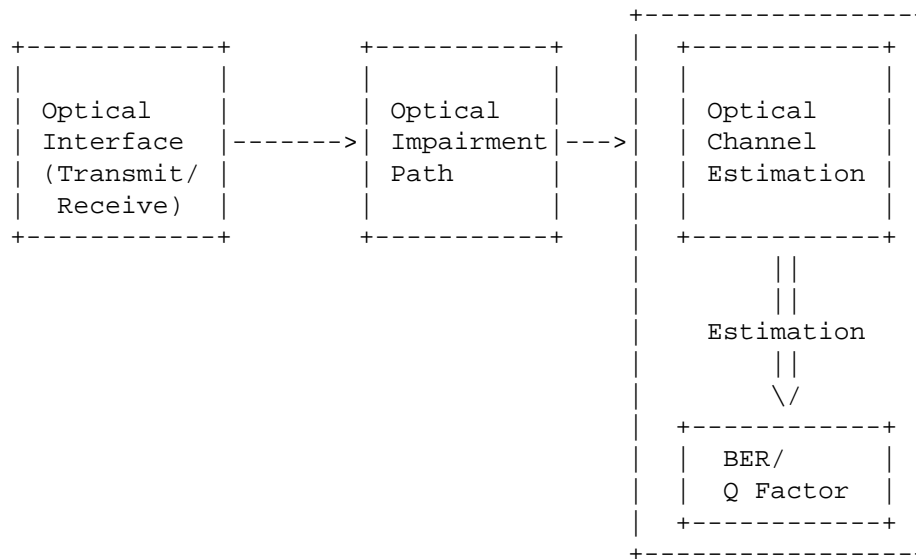
   Starting from the functional block on the left, the optical interface
   represents where the optical signal is transmitted or received and
   defines the properties at the path endpoints. Even the impairment-
   free case, such as scenario B in Section 4.1.1, needs to consider a
   minimum set of interface 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:

   o 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.

   o 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.

   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.

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

   o 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.

   o 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:

   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 improved efficiency.

   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.

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:

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

   o 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)
```
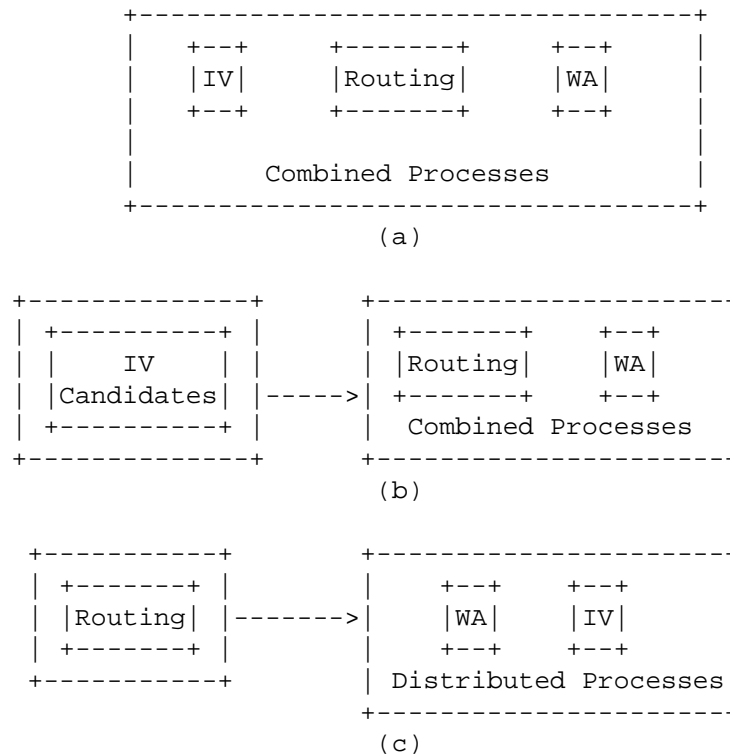
   Figure 2. Process Flows for the Three Main Approximate Impairment
                     Architectural Alternatives

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

   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 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.

   o 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)
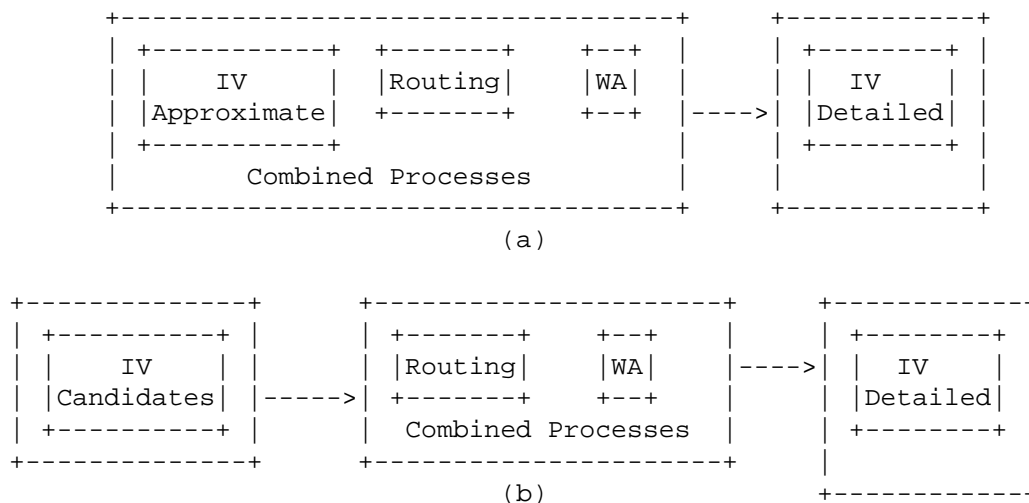
     +--------------+   +----------------------+   +------------+
     | +----------+ | | +-------+   +--+ | | +--------+ |
     | | IV | | | |Routing| |WA| |---->| | IV | |
     | |Candidates| |----->| +-------+   +--+ | | |Detailed| |
     | +----------+ | | Combined Processes | | +--------+ |
     +--------------+   +----------------------+ | |
                            (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.

   o  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  | Yes | No  |    Yes    |   Yes   |
|          IV & RWA  |     |     |           |         |
+--------------------+-----+-----+-----------+---------+
|      IV-Candidates | Yes | No  |    Yes    |   Yes   |
|          + RWA     |     |     |           |         |
+--------------------+-----+-----+-----------+---------+
|        Routing +   | No  | Yes |    Yes    |   No    |
|Distributed IV, RWA |     |     |           |         |
+--------------------+-----+-----+-----------+---------+
```

       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.

   o Traffic Engineering (TE) Database requirements: WSON topology and
      switching capabilities, WSON WDM link wavelength utilization, and
      WSON impairment information.

   o PCC to PCE Request Information: Signal characteristics/type,
      required quality, source node, and destination node.

   o 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.

      o 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|
      +-+-+                 +------+------+         +---------+-------+
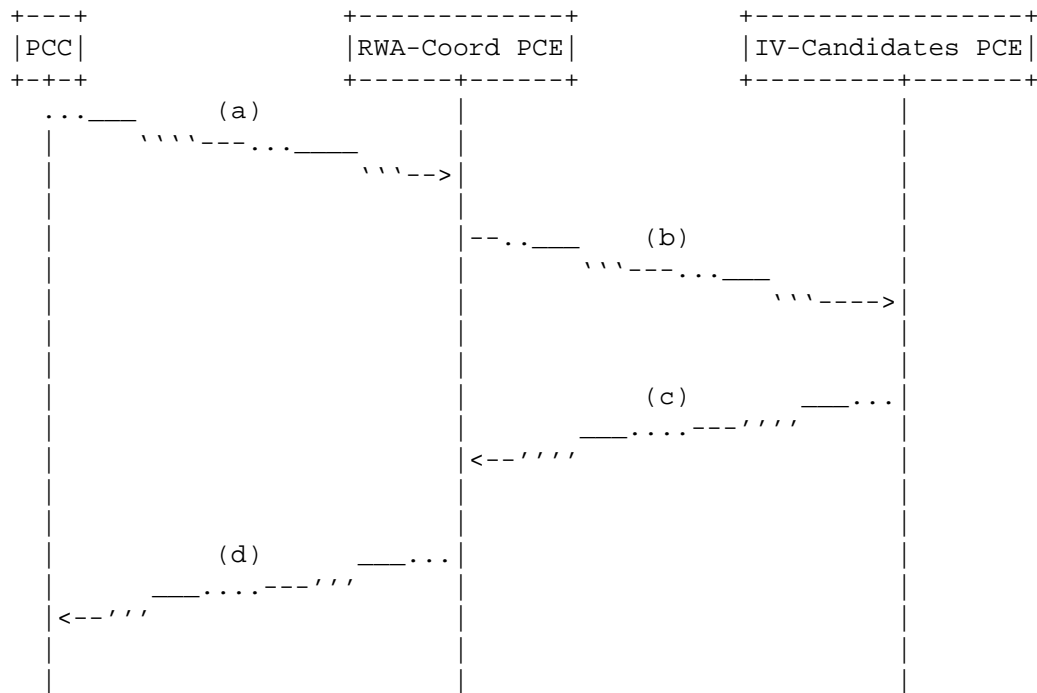        |...___      (a)           |                         |
        |     ````---...____       |                         |
        |                   ```-->|                         |
        |                         |                         |
        |                         |--..___      (b)          |
        |                         |      ```---...___        |
        |                         |                ```---->|
        |                         |                         |
        |                         |                         |
        |                         |          (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:

   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 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.

   o 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.

```
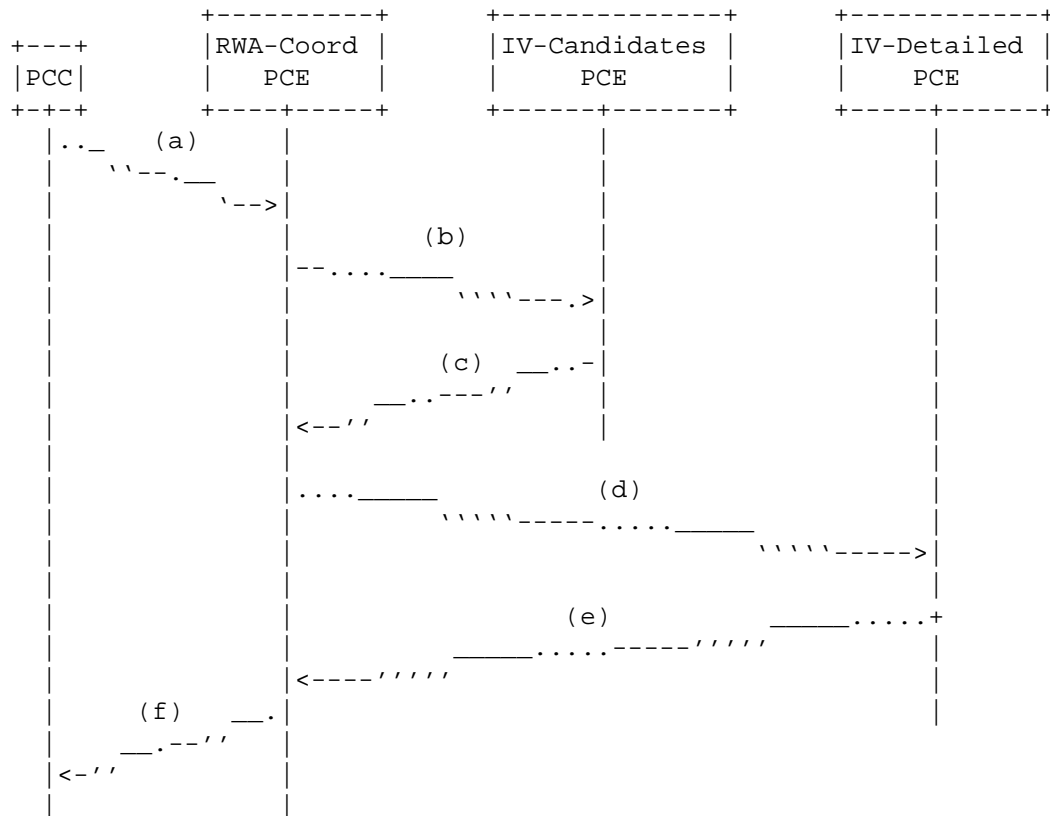                   +----------+     +--------------+     +------------+
       +---+       |RWA-Coord |     |IV-Candidates |     |IV-Detailed |
       |PCC|       |   PCE    |     |     PCE      |     |    PCE     |
       +-+-+       +----+-----+     +------+------+      +-----+------+
         |..__    (a)    |                 |                   |
         |   ``--.__     |                 |                   |
         |          `-->|                  |                   |
         |              |         (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

8.1. Normative References

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