Network Working Group
Internet Draft
Category: Informational
Expiration Date: October 2005

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April 2005

Analysis of Generalized Multi-Protocol Label Switching (GMPLS)-based Recovery Mechanisms (including Protection and Restoration)

draft-ietf-ccamp-gmpls-recovery-analysis-05.txt

Status of this Memo

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Abstract

This document provides an analysis grid to evaluate, compare and contrast the Generalized Multi-Protocol Label Switching (GMPLS) protocol suite capabilities with respect to the recovery mechanisms currently proposed at the IETF CCAMP Working Group. A detailed analysis of each of the recovery phases is provided using the terminology defined in a companion document. This document focuses on transport plane survivability and recovery issues and not on

control plane resilience and related aspects.

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2. Conventions used in this document

The key words "MUST", "MUST NOT", "REQUIRED", "SHALL", "SHALL NOT", "SHOULD", "SHOULD NOT", "RECOMMENDED", "MAY", and "OPTIONAL" in this document are to be interpreted as described in [RFC2119].

Any other recovery-related terminology used in this document conforms to the one defined in [TERM]. The reader is also assumed to be familiar with the terminology developed in [RFC3945], [RFC3471], [RFC3473], [GMPLS-RTG] and [LMP].

3. Introduction

This document provides an analysis grid to evaluate, compare and contrast the Generalized MPLS (GMPLS) protocol suite capabilities with respect to the recovery mechanisms proposed at the IETF CCAMP Working Group. The focus is on transport plane survivability and recovery issues and not on control plane resilience related aspects. Although the recovery mechanisms described in this document impose different requirements on GMPLS-based recovery protocols, the protocol(s) specifications will not be covered in this document. Though the concepts discussed are technology independent, this document implicitly focuses on SONET [T1.105]/SDH [G.707], Optical Transport Networks (OTN) [G.709] and pre-OTN technologies except when specific details need to be considered (for instance, in the case of failure detection).

A detailed analysis is provided for each of the recovery phases as identified in [TERM]. These phases define the sequence of generic

operations that need to be performed when a LSP/Span failure (or any other event generating such failures) occurs:

- Phase 1: Failure detection
- Phase 2: Failure localization and isolation
- Phase 3: Failure notification
- Phase 4: Recovery (Protection/Restoration)
- Phase 5: Reversion (normalization)

Failure detection, localization and notification phases together are referred to as fault management. Within a recovery domain, the entities involved during the recovery operations are defined in [TERM]; these entities include ingress, egress and intermediate nodes. The term "recovery mechanism" is used to cover both protection and restoration mechanisms. Specific terms such as protection and restoration are only used when differentiation is required. Likewise the term "failure" is used to represent both signal failure and signal degradation.

In addition, a clear distinction is made between partitioning (horizontal hierarchy) and layering (vertical hierarchy) when analyzing the different hierarchical recovery mechanisms including disjointness related issues. The dimensions from which each of the recovery mechanisms detailed in this document can be analyzed are

introduced to assess the current GMPLS protocol capabilities and the potential need for further extensions. This document concludes by detailing the applicability of the current GMPLS protocol building blocks for recovery purposes.

4. Fault Management

4.1 Failure Detection

Transport failure detection is the only phase that can not be achieved by the control plane alone since the latter needs a hook to the transport plane to collect the related information. It has to be emphasized that even if failure events themselves are detected by the transport plane, the latter, upon a failure condition, must trigger the control plane for subsequent actions through the use of GMPLS signalling capabilities (see [RFC3471] and [RFC3473]) or Link Management Protocol capabilities (see [LMP], Section 6).

Therefore, by definition, transport failure detection is transport technology dependent (and so exceptionally, we keep here the "transport plane" terminology). In transport fault management, distinction is made between a defect and a failure. Here, the

discussion addresses failure detection (persistent fault cause). In the technology-dependent descriptions, a more precise specification will be provided.

As an example, SONET/SDH (see [G.707], [G.783] and [G.806]) provides supervision capabilities covering:

- Continuity: monitors the integrity of the continuity of a trail (i.e. section or path). This operation is performed by monitoring the presence/absence of the signal. Examples are Loss of Signal (LOS) detection for the physical layer, Unequipped (UNEQ) Signal detection for the path layer, Server Signal Fail Detection (e.g. AIS) at the client layer.

- Connectivity: monitors the integrity of the routing of the signal between end-points. Connectivity monitoring is needed if the layer provides flexible connectivity, either automatically (e.g. cross-connects) or manually (e.g. fiber distribution frame). An example is the Trail (i.e. section or path) Trace Identifier used at the different layers and the corresponding Trail Trace Identifier Mismatch detection.

- Alignment: checks that the client and server layer frame start can be correctly recovered from the detection of loss of alignment. The specific processes depend on the signal/frame structure and may include: (multi-)frame alignment, pointer processing and alignment of several independent frames to a common frame start in case of inverse multiplexing. Loss of alignment is a generic term. Examples are loss of frame, loss of multi-frame, or loss of pointer.

- Payload type: checks that compatible adaptation functions are used at the source and the destination. This is normally done by adding a payload type identifier (referred to as the "signal label") at the source adaptation function and comparing it with the expected identifier at the destination. For instance, the payload type identifier and the corresponding mismatch detection.

- Signal Quality: monitors the performance of a signal. For instance, if the performance falls below a certain threshold a defect - excessive errors (EXC) or degraded signal (DEG) - is detected.

The most important point is that the supervision processes and the corresponding failure detection (used to initiate the recovery

phase(s)) result in either:

- Signal Degrade (SD): A signal indicating that the associated data has degraded in the sense that a degraded defect condition is active (for instance, a dDEG declared when the Bit Error Rate exceeds a preset threshold).

- Signal Fail (SF): A signal indicating that the associated data has failed in the sense that a signal interrupting near-end defect condition is active (as opposed to the degraded defect).

In Optical Transport Networks (OTN) equivalent supervision capabilities are provided at the optical/digital section layers (i.e. Optical Transmission Section (OTS), Optical Multiplex Section (OMS) and Optical channel Transport Unit (OTU)) and at the optical/digital path layers (i.e. Optical Channel (OCh) and Optical channel Data Unit (ODU)). Interested readers are referred to the ITU-T Recommendations [G.798] and [G.709] for more details.

The above are examples that illustrate cases where the failure detection, and reporting entities (see [TERM]) are co-located. The following example illustrates the scenario where the failure detecting and reporting entities (see [TERM]) are not co-located.

In pre-OTN networks, a failure may be masked by intermediate O-E-O based Optical Line System (OLS), preventing a Photonic Cross-Connect (PXC) from detecting upstream failures. In such cases, failure detection may be assisted by an out-of-band communication channel and failure condition reported to the PXC control plane. This can be provided by using [LMP-WDM] extensions that delivers IP message-based communication between the PXC and the OLS control plane. Also, since PXCs are independent of the framing format, failure conditions can only be triggered either by detecting the absence of the optical signal or by measuring its quality. These mechanisms are generally less reliable than electrical (digital) ones. Both types of detection mechanisms are outside the scope of this document. If the intermediate OLS supports electrical (digital) mechanisms, using the LMP communication channel, these failure conditions are reported to

the PXC and subsequent recovery actions performed as described in Section 5. As such from the control plane viewpoint, this mechanism turn the OLS-PXC composed system into a single logical entity allowing the consideration of the same failure management mechanisms for such entity as for any other O-E-O capable device.

More generally, the following are typical failure conditions in SONET/SDH and pre-OTN networks:

- Loss of Light (LOL)/Loss of Signal (LOS): Signal Failure (SF) condition where the optical signal is not detected any longer on the receiver of a given interface.
- Signal Degrade (SD): detection of the signal degradation over a specific period of time.
- For SONET/SDH payloads, all of the above-mentioned supervision capabilities can be used, resulting in SD or SF condition.

In summary, the following cases apply when considering the communication between the detecting and reporting entities:

- Co-located detecting and reporting entities: both the detecting and reporting entities are on the same node (e.g., SONET/SDH equipment, Opaque cross-connects, and, with some limitations, Transparent cross-connects, etc.)

- Non co-located detecting and reporting entities:
  o with in-band communication between entities: entities are physically separated but the transport plane provides in-band communication between them (e.g., Server Signal Failures (Alarm Indication Signal (AIS)), etc.)
  o with out-of-band communication between entities: entities are physically separated but an out-of-band communication channel is provided between them (e.g., using [LMP]).

4.2 Failure Localization and Isolation

Failure localization provides to the deciding entity information about the location (and so the identity) of the transport plane entity that detects the LSP(s)/span(s) failure. The deciding entity can then make an accurate decision to achieve finer grained recovery switching action(s). Note that this information can also be included as part of the failure notification (see Section 4.3).

In some cases, this accurate failure localization information may be less urgent to determine if it requires performing more time consuming failure isolation (see also Section 4.4). This is particularly the case when edge-to-edge LSP recovery (edge referring to a sub-network end-node for instance) is performed based on a simple failure notification (including the identification of the working LSPs under failure condition). In this case, a more accurate localization and isolation can be performed after recovery of these LSPs.

Failure localization should be triggered immediately after the fault

detection phase. This operation can be performed at the transport plane and/or, if unavailable (via the transport plane), the control plane level where dedicated signaling messages can be used. When performed at the control plane level, a protocol such as LMP (see [LMP], Section 6) can be used for failure localization purposes.

4.3 Failure Notification

Failure notification is used 1) to inform intermediate nodes that an LSP/span failure has occurred and has been detected 2) to inform the deciding entities (which can correspond to any intermediate or end-point of the failed LSP/span) that the corresponding service is not available. In general, these deciding entities will be the ones taking the appropriate recovery decision. When co-located with the recovering entity, these entities will also perform the corresponding recovery action(s).

Failure notification can be either provided by the transport or by the control plane. As an example, let us first briefly describe the failure notification mechanism defined at the SONET/SDH transport plane level (also referred to as maintenance signal supervision):

- AIS (Alarm Indication Signal) occurs as a result of a failure condition such as Loss of Signal and is used to notify downstream nodes (of the appropriate layer processing) that a failure has occurred. AIS performs two functions 1) inform the intermediate nodes (with the appropriate layer monitoring capability) that a failure has been detected 2) notify the connection end-point that the service is no longer available.

For a distributed control plane supporting one (or more) failure notification mechanism(s), regardless of the mechanism's actual implementation, the same capabilities are needed with more (or less) information provided about the LSPs/spans under failure condition, their detailed status, etc.

The most important difference between these mechanisms is related to the fact that transport plane notifications (as defined today) would directly initiate either a certain type of protection switching (such as those described in [TERM]) via the transport plane or restoration actions via the management plane.

On the other hand, using a failure notification mechanism through the control plane would provide the possibility to trigger either a protection or a restoration action via the control plane. This has the advantage that a control plane recovery responsible entity does not necessarily have to be co-located with a transport maintenance/recovery domain. A control plane recovery domain can be defined at entities not supporting a transport plane recovery.

Moreover, as specified in [RFC3473], notification message exchanges

through a GMPLS control plane may not follow the same path as the

LSP/spans for which these messages carry the status. In turn, this ensures a fast, reliable (through acknowledgement and the use of either a dedicated control plane network or disjoint control channels) and efficient (through the aggregation of several LSP/span status within the same message) failure notification mechanism.

The other important properties to be met by the failure notification mechanism are mainly the following:

- Notification messages must provide enough information such that the most efficient subsequent recovery action will be taken (in most of the recovery types and schemes this action is even deterministic) at the recovering entities. Remember here that these entities can be either intermediate or end-points through which normal traffic flows. Based on local policy, intermediate nodes may not use this information for subsequent recovery actions (see for instance the APS protocol phases as described in [TERM]). In addition, since fast notification is a mechanism running in collaboration with the existing GMPLS signalling (see [RFC3473]) that also allows intermediate nodes to stay informed about the status of the working LSP/spans under failure condition.

  The trade-off here is to define what information the LSP/span end-points (more precisely, the deciding entity) needs in order for the recovering entity to take the best recovery action: if not enough information is provided, the decision can not be optimal (note that in this eventuality, the important issue is to quantify the level of sub-optimality), if too much information is provided the control plane may be overloaded with unnecessary information and the aggregation/correlation of this notification information will be more complex and time consuming to achieve. Note that a more detailed quantification of the amount of information to be exchanged and processed is strongly dependent on the failure notification protocol.

- If the failure localization and isolation is not performed by one of the LSP/span end-points or some intermediate points, they should receive enough information from the notification message in order to locate the failure otherwise they would need to (re-) initiate a failure localization and isolation action.

- Avoiding so-called notification storms implies that 1) the failure detection output is correlated (i.e. alarm correlation) and aggregated at the node detecting the failure(s) 2) the failure

notifications are directed to a restricted set of destinations (in general the end-points) and that 3) failure notification suppression (i.e. alarm suppression) is provided in order to limit flooding in case of multiple and/or correlated failures appearing at several locations in the network.

- Alarm correlation and aggregation (at the failure detecting node) implies a consistent decision based on the conditions for which a trade-off between fast convergence (at detecting node) and

fast notification (implying that correlation and aggregation occurs at receiving end-points) can be found.

4.4 Failure Correlation

A single failure event (such as a span failure) can result into reporting multiple failures (such as individual LSP failures) conditions. These can be grouped (i.e. correlated) to reduce the number of failure conditions communicated on the reporting channel, for both in-band and out-of-band failure reporting.

In such a scenario, it can be important to wait for a certain period of time, typically called failure correlation time, and gather all the failures to report them as a group of failures (or simply group failure). For instance, this approach can be provided using LMP-WDM for pre-OTN networks (see [LMP-WDM]) or when using Signal Failure/ Degrade Group in the SONET/SDH context.

Note that a default average time interval during which failure correlation operation can be performed is difficult to provide since it is strongly dependent on the underlying network topology. Therefore, it can be advisable to provide a per-node configurable failure correlation time. The detailed selection criteria for this time interval are outside of the scope of this document.

When failure correlation is not provided, multiple failure notification messages may be sent out in response to a single failure (for instance, a fiber cut), each one containing a set of information on the failed working resources (for instance, the individual lambda LSP flowing through this fiber). This allows for a more prompt response but can potentially overload the control plane due to a large amount of failure notifications.

5. Recovery Mechanisms

5.1 Transport vs. Control Plane Responsibilities

For both protection and restoration, and when applicable, recovery resources are provisioned using GMPLS signalling capabilities. Thus, these are control plane-driven actions (topological and resource-constrained) that are always performed in this context.

The following tables give an overview of the responsibilities taken by the control plane in case of LSP/span recovery:

1. LSP/span Protection

- Phase 1: Failure detection — Transport plane
- Phase 2: Failure localization/isolation — Transport/Control plane
- Phase 3: Failure notification — Transport/Control plane
- Phase 4: Protection switching — Transport/Control plane
- Phase 5: Reversion (normalization) — Transport/Control plane

Note: in the context of LSP/span protection, control plane actions can be performed either for operational purposes and/or synchronization purposes (vertical synchronization between transport and control plane) and/or notification purposes (horizontal synchronization between end-nodes at control plane level). This suggests the selection of the responsible plane (in particular for protection switching) during the provisioning phase of the protected/protection LSP.

2. LSP/span Restoration

- Phase 1: Failure detection — Transport plane
- Phase 2: Failure localization/isolation — Transport/Control plane
- Phase 3: Failure notification — Control plane
- Phase 4: Recovery switching — Control plane
- Phase 5: Reversion (normalization) — Control plane

Therefore, this document primarily focuses on provisioning of LSP recovery resources, failure notification mechanisms, recovery switching, and reversion operations. Moreover some additional considerations can be dedicated to the mechanisms associated to the failure localization/isolation phase.

5.2 Technology in/dependent mechanisms

The present recovery mechanisms analysis applies in fact to any circuit oriented data plane technology with discrete bandwidth increments (like SONET/SDH, G.709 OTN, etc.) being controlled by a GMPLS-based distributed control plane.

The following sub-sections are not intended to favor one technology versus another. They just list pro and cons for each of them in order to determine the mechanisms that GMPLS-based recovery must deliver to overcome their cons and take benefits of their pros in their respective applicability context.

5.2.1 OTN Recovery

OTN recovery specifics are left for further considerations.

5.2.2 Pre-OTN Recovery

Pre-OTN recovery specifics (also referred to as "lambda switching") present mainly the following advantages:

- benefits from a simpler architecture making it more suitable for mesh-based recovery types and schemes (on a per channel basis).

- when providing suppression of intermediate node transponders (vs. use of non-standard masking of upstream failures) e.g. use of squelching, implies that failures (such as LoL) will propagate to edge nodes giving the possibility to initiate recovery actions driven by upper layers.

The main disadvantage comes from the lack of interworking due to the large amount of failure management (in particular failure notification protocols) and recovery mechanisms currently available.

Note also, that for all-optical networks, combination of recovery with optical physical impairments is left for a future release of this document since corresponding detection technologies are under specification.

5.2.3 SONET/SDH Recovery

Some of the advantages of SONET [T1.105]/SDH [G.707] and more generically any TDM transport plane recovery are that they provide:

- Protection types operating at the data plane level are standardized (see [G.841]) and can operate across protected domains and interwork (see [G.842]).

- Failure detection, notification and path/section Automatic Protection Switching (APS) mechanisms.

- Greater control over the granularity of the TDM LSPs/links that

can be recovered with respect to coarser optical channel (or whole fiber content) recovery switching

Some of the limitations of the SONET/SDH recovery are:

- Limited topological scope: Inherently the use of ring topologies, typically, dedicated Sub-Network Connection Protection (SNCP) or shared protection rings, has reduced flexibility and resource efficiency with respect to the (somewhat more complex) meshed recovery.

- Inefficient use of spare capacity: SONET/SDH protection is largely applied to ring topologies, where spare capacity often remains idle, making the efficiency of bandwidth usage a real issue.

- Support of meshed recovery requires intensive network management development and the functionality is limited by both the network elements and the capabilities of the element management systems (justifying thus the development of GMPLS-based distributed recovery mechanisms.)

5.3 Specific Aspects of Control Plane-based Recovery Mechanisms

5.3.1 In-band vs Out-of-band Signalling

The nodes communicate through the use of IP terminating control channels defining the control plane (transport) topology. In this context, two classes of transport mechanisms can be considered here i.e. in-fiber or out-of-fiber (through a dedicated physically diverse control network referred to as the Data Communication

Network or DCN). The potential impact of the usage of an in-fiber (signalling) transport mechanism is briefly considered here.

In-fiber transport mechanism can be further subdivided into in-band and out-of-band. As such, the distinction between in-fiber in-band and in-fiber out-of-band signalling reduces to the consideration of a logically versus physically embedded control plane topology with respect to the transport plane topology. In the scope of this document, it is assumed that at least one IP control channel between each pair of adjacent nodes is continuously available to enable the exchange of recovery-related information and messages. Thus, in either case (i.e. in-band or out-of-band) at least one logical or physical control channel between each pair of nodes is always expected to be available.

Therefore, the key issue when using in-fiber signalling is whether

one can assume independence between the fault-tolerance capabilities of control plane and the failures affecting the transport plane (including the nodes). Note also that existing specifications like the OTN provide a limited form of independence for in-fiber signaling by dedicating a separate optical supervisory channel (OSC, see [G.709] and [G.874]) to transport the overhead and other control traffic. For OTNs, failure of the OSC does not result in failing the optical channels. Similarly, loss of the control channel must not result in failing the data channels (transport plane).

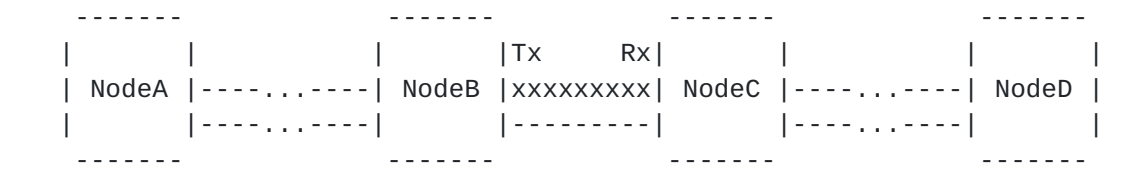
5.3.2 Uni- versus Bi-directional Failures

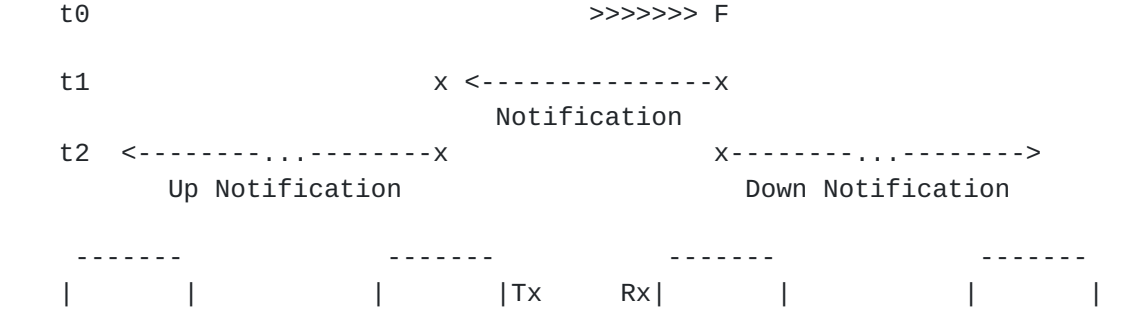
The failure detection, correlation and notification mechanisms (described in Section 4) can be triggered when either a unidirectional or a bi-directional LSP/Span failure occurs (or a combination of both). As illustrated in Figure 1 and 2, two alternatives can be considered here:

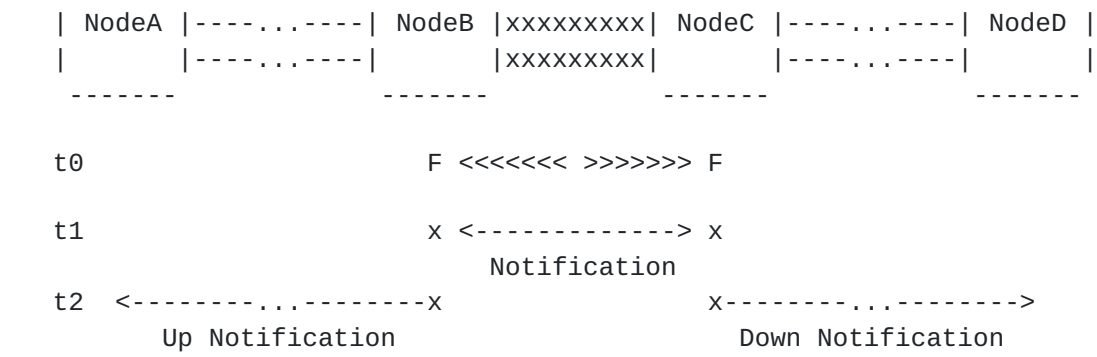
1. Uni-directional failure detection: the failure is detected on the receiver side i.e. it is only is detected by the downstream node to the failure (or by the upstream node depending on the failure propagation direction, respectively).

2. Bi-directional failure detection: the failure is detected on the receiver side of both downstream node AND upstream node to the failure.

Notice that after the failure detection time, if only control plane based failure management is provided, the peering node is unaware of the failure detection status of its neighbor.







After failure detection, the following failure management operations can be subsequently considered:

- Each detecting entity sends a notification message to the corresponding transmitting entity. For instance, in Fig. 1 (Fig. 2), node C sends a notification message to node B (while node B sends a notification message to node C). To ensure reliable failure notification, a dedicated acknowledgment message can be returned back to the sender node.

- Next, within a certain (and pre-determined) time window, nodes impacted by the failure occurrences may perform their correlation. In case of unidirectional failure, node B only receives the notification message from node C and thus the time for this operation is negligible. In case of bi-directional failure, node B (and node C) has to correlate the received notification message from node C (node B, respectively) with the corresponding locally detected information.

- After some (pre-determined) period of time, referred to as the hold-off time, after which the local recovery actions (see Section 5.3.4) were not successful, the following occurs. In case of unidirectional failure and depending on the directionality of the LSP, node B should send an upstream notification message (see [RFC3473]) to the ingress node A and node C may send a downstream notification message (see [RFC3473]) to the egress node D. However, in such a case only node A referred to as the "master" (node D being then referred to as the "slave" per [TERM]), would initiate an edge to edge recovery action. Note that the other LSP end-node (i.e. node D in this case) may be optionally notified using a downstream notification message (see [RFC3473]).

  In case of bi-directional failure, node B should send an upstream

  notification message (see [RFC3473]) to the ingress node A and node C may send a downstream notification message (see [RFC3473])

to the egress node D. However, due to the dependence on the LSP directionality, only ingress node A would initiate an edge to edge recovery action. Note that the other LSP end-node (i.e. node D in this case) should also be notified of this event using a downstream notification message (see [RFC3473]). For instance, if an LSP directed from D to A is under failure condition, only the notification message sent from node C to D would initiate a recovery action and, in this case, per [TERM], the deciding and recovering node D is referred to as the "master" while node A is referred to as the "slave" (i.e. recovering only entity).

Note: The determination of the master and the slave may be based either on configured information or dedicated protocol capability.

In the above scenarios, the path followed by the upstream and downstream notification messages does not have to be the same as the one followed by the failed LSP (see [RFC3473] for more details on the notification message exchange). The important point, concerning this mechanism, is that either the detecting/reporting entity (i.e. the nodes B and C) is also the deciding/recovery entity or the detecting/reporting entity is simply an intermediate node in the subsequent recovery process. One refers to local recovery in the former case and to edge-to-edge recovery in the latter one (see also Section 5.3.4).

5.3.3 Partial versus Full Span Recovery

When a given span carries more than one LSPs or LSP segments, an additional aspect must be considered. In case of span failure, the LSPs it carries can be either individually recovered or recovered as a group (aka bulk LSP recovery) or independent sub-groups. The selection of this mechanism would be triggered independently of the failure notification granularity when correlation time windows are used and simultaneous recovery of several LSPs can be performed using a single request. Moreover, criteria by which such sub-groups can be formed are outside of the scope of this document.

Additional complexity arises in the case of (sub-)group LSP recovery. Between a given pair of nodes, the LSPs that a given (sub-)group contains may have been created from different source nodes (i.e. initiator) and directed toward different destinations nodes. Consequently the failure notification messages sub-sequent to a bi-directional span failure affecting several LSPs (or the whole group of LSPs it carries) are not necessarily directed toward the same initiator nodes. In particular these messages may be directed to both the upstream and downstream nodes to the failure. Therefore, such span failure may trigger recovery actions to be performed from both sides (i.e. both from the upstream and the downstream node to the failure). In order to facilitate the definition of the corresponding recovery mechanisms (and their sequence), one assumes here as well, that per [TERM] the deciding (and recovering) entity,

referred to as the "master" is the only initiator of the recovery of the whole LSP (sub-)group.

5.3.4 Difference between LSP, LSP Segment and Span Recovery

The recovery definitions given in [TERM] are quite generic and apply for link (or local span) and LSP recovery. The major difference between LSP, LSP Segment and span recovery is related to the number of intermediate nodes that the signalling messages have to travel. Since nodes are not necessarily adjacent in case of LSP (or LSP Segment) recovery, signalling message exchanges from the reporting to the deciding/recovery entity may have to cross several intermediate nodes. In particular, this applies for the notification messages due to the number of hops separating the location of a failure occurrence from its destination. This results in an additional propagation and forwarding delay. Note that the former delay may in certain circumstances be non-negligible; e.g. in case of copper out-of-band network, approximately 1 ms per 200km.

Moreover, the recovery mechanisms applicable to end-to-end LSPs and to the segments that may compose an end-to-end LSP (i.e. edge-to-edge recovery) can be exactly the same. However, one expects in the latter case, that the destination of the failure notification message will be the ingress/egress of each of these segments. Therefore, using the mechanisms described in Section 5.3.2, failure notification messages can be first exchanged between terminating points of the LSP segment and after expiration of the hold-off time be directed toward terminating points of the end-to-end LSP.

Note: Several studies provide quantitative analysis of the relative performance of LSP/span recovery techniques. [WANG] for instance, provides an analysis grid for these techniques showing that dynamic LSP restoration (see Section 5.5.2) performs well under medium network loads but suffers performance degradations at higher loads due to greater contention for recovery resources. LSP restoration upon span failure, as defined in [WANG], degrades at higher loads because paths around failed links tend to increase the hop count of the affected LSPs and thus consume additional network resources. Also, performance of LSP restoration can be enhanced by a failed working LSP's source node initiating a new recovery attempt if an initial attempt fails. A single retry attempt is sufficient to produce large increases in the restoration success rate and ability to initiate successful LSP restoration attempts, especially at high loads, while not adding significantly to the long-term average recovery time. Allowing additional attempts produces only small

additional gains in performance. This suggests using additional (intermediate) crankback signalling when using dynamic LSP restoration (described in Section 5.5.2 - case 2). Details on crankback signalling are outside the scope of the present document.

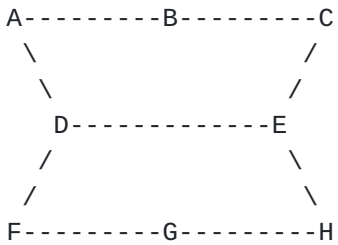
5.4 Difference between Recovery Type and Scheme

[TERM] defines the basic LSP/span recovery types. This section describes the recovery schemes that can be built using these recovery types. In brief, a recovery scheme is defined as the combination of several ingress-egress node pairs supporting a given recovery type (from the set of the recovery types they allow). Several examples are provided here to illustrate the difference between recovery types such as 1:1 or M:N and recovery schemes such as (1:1)^n or (M:N)^n referred to as shared-mesh recovery.

1. (1:1)^n with recovery resource sharing

The exponent, n, indicates the number of times a 1:1 recovery type is applied between at most n different ingress-egress node pairs. Here, at most n pairs of disjoint working and recovery LSPs/spans share at most n times a common resource. Since the working LSPs/spans are mutually disjoint, simultaneous requests for use of the shared (common) resource will only occur in case of simultaneous failures, which is less likely to happen.

For instance, in the common (1:1)^2 case, if the 2 recovery LSPs in the group overlap the same common resource, then it can handle only single failures; any multiple working LSP failures will cause at least one working LSP to be denied automatic recovery. Consider for instance the following topology with the working LSPs A-B-C and F-G-H and their respective recovery LSPs A-D-E-C and F-D-E-H that share a common D-E link resource.

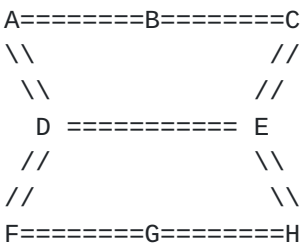


2. (M:N)^n with recovery resource sharing

The (M:N)^n scheme is documented here for the sake of completeness only (i.e. it is not mandated that GMPLS capabilities would support this scheme). The exponent, n, indicates the number of times an M:N recovery type is applied between at most n different ingress-egress node pairs. So the interpretation follows from the previous case, except that here disjointness applies to the N working LSPs/spans and to the M recovery LSPs/spans while sharing at most n times M common resources.

In both schemes, it results in a "group" of sum{n=1}^N N{n} working LSPs and a pool of shared recovery resources, not all of which are available to any given working LSP. In such conditions, defining a metric that describes the amount of overlap among the recovery LSPs would give some indication of the group's ability to handle simultaneous failures of multiple LSPs.

For instance, in the simple (1:1)^n case, if n recovery LSPs in a (1:1)^n group overlap, then it can handle only single failures; any simultaneous failure of multiple working LSPs will cause at least one working LSP to be denied automatic recovery. But if one considers for instance, a (2:2)^2 group in which there are two pairs of overlapping recovery LSPs, then two LSPs (belonging to the same pair) can be simultaneously recovered. The latter case can be illustrated by the following topology with 2 pairs of working LSPs A-B-C and F-G-H and their respective recovery LSPs A-D-E-C and F-D-E-H that share two common D-E link resources.



Moreover, in all these schemes, (working) path disjointness can be enforced by exchanging information related to working LSPs during the recovery LSP signaling. Specific issues related to the combination of shared (discrete) bandwidth and disjointness for recovery schemes are described in Section 8.4.2.

5.5 LSP Recovery Mechanisms

5.5.1 Classification

The recovery time and ratio of LSPs/spans depend on proper recovery LSP provisioning (meaning pre-provisioning when performed before failure occurrence) and the level of overbooking of recovery resources (i.e. over-provisioning). A proper balance of these two operations will result in the desired LSP/span recovery time and ratio when single or multiple failure(s) occur(s). Note also that these operations are mostly performed during the network planning phases.

The different options for LSP (pre-)provisioning and overbooking are classified below to structure the analysis of the different recovery mechanisms.

1. Pre-Provisioning

Proper recovery LSP pre-provisioning will help to alleviate the failure of the working LSPs (due to the failure of the resources that carry these LSPs). As an example, one may compute and establish the recovery LSP either end-to-end or segment-per-segment, to protect a working LSP from multiple failure events affecting

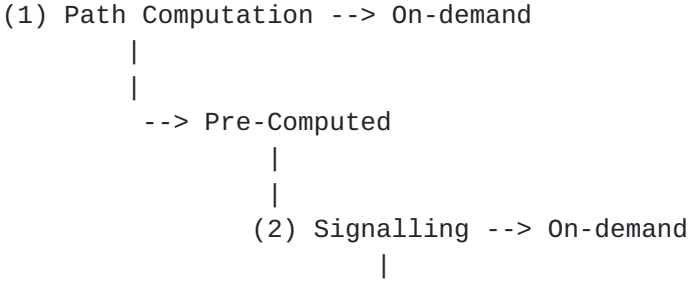
link(s), node(s) and/or SRLG(s). The recovery LSP pre-provisioning options can be classified (in the below figure) as follows:

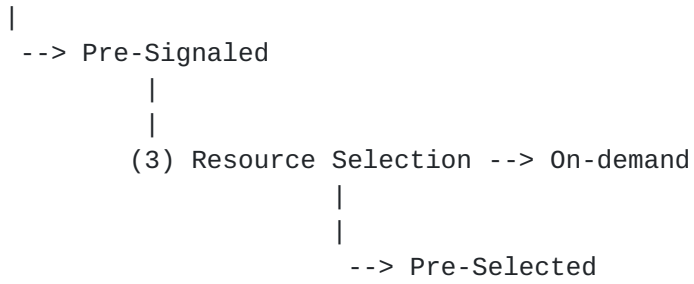
(1) the recovery path can be either pre-computed or computed on-demand.

(2) when the recovery path is pre-computed, it can be either pre-signaled (implying recovery resource reservation) or signaled on-demand.

(3) when the recovery resources are pre-signaled, they can be either pre-selected or selected on-demand.

Recovery LSP provisioning phases:



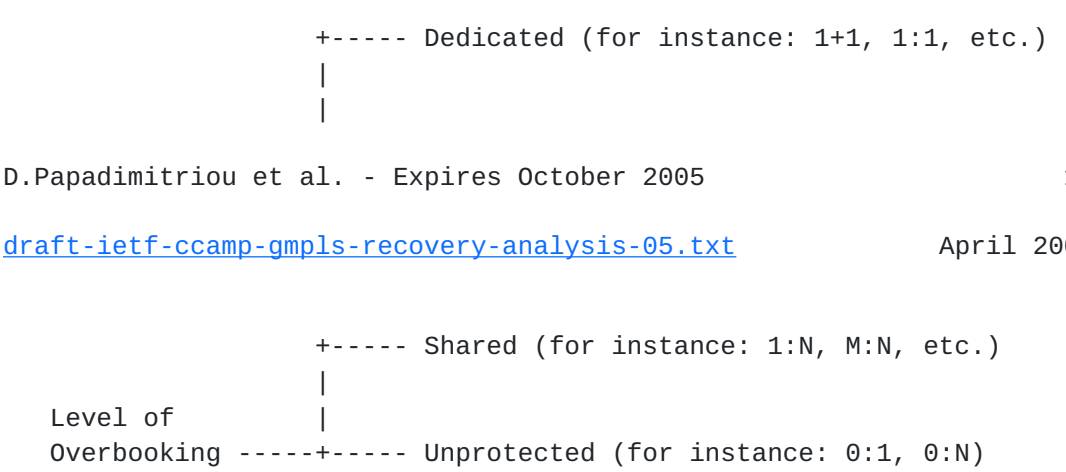


Note that these different options lead to different LSP/span recovery times. The following sections will consider the above-mentioned pre-provisioning options when analyzing the different recovery mechanisms.

2. Overbooking

There are many mechanisms available that allow the overbooking of the recovery resources. This overbooking can be done per LSP (such as the example mentioned above), per link (such as span protection) or even per domain. In all these cases, the level of overbooking, as shown in the below figure, can be classified as dedicated (such as 1+1 and 1:1), shared (such as 1:N and M:N) or unprotected (and thus restorable if enough recovery resources are available).

Overbooking levels:



Also, when using shared recovery, one may support preemptible extra-traffic; the recovery mechanism is then expected to allow preemption of this low priority traffic in case of recovery resource contention during recovery operations. The following sections will consider the above-mentioned overbooking options when analyzing the different recovery mechanisms.

5.5.2 LSP Restoration

The following times are defined to provide a quantitative estimation about the time performance of the different LSP restoration

mechanisms (also referred to as LSP re-routing):

- Path Computation Time: Tc
- Path Selection Time: Ts
- End-to-end LSP Resource Reservation Time: Tr (a delta for resource selection is also considered, the corresponding total time is then referred to as Trs)
- End-to-end LSP Resource Activation Time: Ta (a delta for resource selection is also considered, the corresponding total time is then referred to as Tas)

The Path Selection Time (Ts) is considered when a pool of recovery LSP paths between a given pair of source/destination end-points is pre-computed and after a failure occurrence one of these paths is selected for the recovery of the LSP under failure condition.

Note: failure management operations such as failure detection, correlation and notification are considered (for a given failure event) as equally time consuming for all the mechanisms described here below:

1. With Route Pre-computation (or LSP re-provisioning)

An end-to-end restoration LSP is established after the failure(s) occur(s) based on a pre-computed path. As such, one can define this as an "LSP re-provisioning" mechanism. Here, one or more (disjoint) paths for the restoration LSP are computed (and optionally pre-selected) before a failure occurs.

No reservation or selection of resources is performed along the restoration path before failure occurrence. As a result, there is no guarantee that a restoration LSP is available when a failure occurs.

The expected total restoration time T is thus equal to Ts + Trs or to Trs when a dedicated computation is performed for each working LSP.

2. Without Route Pre-computation (or Full LSP re-routing)

An end-to-end restoration LSP is dynamically established after the failure(s) occur(s). Here, after failure occurrence, one or more (disjoint) paths for the restoration LSP are dynamically computed and one is selected. As such, one can define this as a complete "LSP re-routing" mechanism.

No reservation or selection of resources is performed along the

restoration path before failure occurrence. As a result, there is no guarantee that a restoration LSP is available when a failure occurs.

The expected total restoration time T is thus equal to Tc (+ Ts) + Trs. Therefore, time performance between these two approaches differs by the time required for route computation Tc (and its potential selection time, Ts).

5.5.3 Pre-planned LSP Restoration

Pre-planned LSP restoration (also referred to as pre-planned LSP re-routing) implies that the restoration LSP is pre-signaled. This in turn implies the reservation of recovery resources along the restoration path. Two cases can be defined based on whether the recovery resources are pre-selected or not.

1. With resource reservation and without resource pre-selection

Before failure occurrence, an end-to-end restoration path is pre-selected from a set of pre-computed (disjoint) paths. The restoration LSP is signaled along this pre-selected path to reserve resources at each node but these resources are not selected.

In this case, the resources reserved for each restoration LSP may be dedicated or shared between multiple restoration LSPs whose working LSPs are not expected to fail simultaneously. Local node policies can be applied to define the degree to which these resources can be shared across independent failures. Also, since a restoration scheme is considered, resource sharing should not be limited to restoration LSPs starting and ending at the same ingress and egress nodes. Therefore, each node participating to this scheme is expected to receive some feedback information on the sharing degree of the recovery resource(s) that this scheme involves.

Upon failure detection/notification message reception, signaling is initiated along the restoration path to select the resources, and to perform the appropriate operation at each node crossed by the restoration LSP (e.g. cross-connections). If lower priority LSPs were established using the restoration resources, they must be preempted when the restoration LSP is activated.

The expected total restoration time T is thus equal to Tas (post-failure activation) while operations performed before failure occurrence takes Tc + Ts + Tr.

2. With both resource reservation and resource pre-selection

Before failure occurrence, an end-to-end restoration path is pre-selected from a set of pre-computed (disjoint) paths. The restoration LSP is signaled along this pre-selected path to reserve AND select resources at each node but these resources are not committed at the data plane level. Such that the selection of the recovery resources is committed at the control plane level only, no cross-connections are performed along the restoration path.

In this case, the resources reserved and selected for each restoration LSP may be dedicated or even shared between multiple restoration LSPs whose associated working LSPs are not expected to fail simultaneously. Local node policies can be applied to define the degree to which these resources can be shared across independent failures. Also, since a restoration scheme is considered, resource sharing should not be limited to restoration LSPs starting and ending at the same ingress and egress nodes. Therefore, each node participating to this scheme is expected to receive some feedback information on the sharing degree of the recovery resource(s) that this scheme involves.

Upon failure detection/notification message reception, signaling is initiated along the restoration path to activate the reserved and selected resources, and to perform the appropriate operation at each node crossed by the restoration LSP (e.g. cross-connections). If lower priority LSPs were established using the restoration resources, they must be preempted when the restoration LSP is activated.

The expected total restoration time T is thus equal to Ta (post-failure activation) while operations performed before failure occurrence takes Tc + Ts + Trs. Therefore, time performance between these two approaches differs only by the time required for resource selection during the activation of the recovery LSP (i.e. Tas - Ta).

5.5.4 LSP Segment Restoration

The above approaches can be applied on an edge-to-edge LSP basis rather than end-to-end LSP basis (i.e. to reduce the global recovery time) by allowing the recovery of the individual LSP segments constituting the end-to-end LSP.

Also, by using the horizontal hierarchy approach described in Section 7.1, an end-to-end LSP can be recovered by multiple recovery mechanisms applied on an LSP segment basis (e.g. 1:1 edge-to-edge LSP protection in a metro network and M:N edge-to-edge protection in the core). These mechanisms are ideally independent and may even use different failure localization and notification mechanisms.

6. Reversion

Reversion (a.k.a. normalization) is defined as the mechanism allowing switching of normal traffic from the recovery LSP/span to the working LSP/span previously under failure condition. Use of normalization is at the discretion of the recovery domain policy. Normalization (also referred to as reversion) may impact the normal traffic (a second hit) depending on the normalization mechanism used.

If normalization is supported 1) the LSP/span must be returned to the working LSP/span when the failure condition clears 2) the capability to de-activate (turn-off) the use of reversion should be provided. De-activation of reversion should not impact the normal traffic regardless of whether currently using the working or recovery LSP/span.

Note: during the failure, the reuse of any non-failed resources (e.g. LSP and/or spans) belonging to the working LSP/span is under the discretion of recovery domain policy.

6.1 Wait-To-Restore (WTR)

A specific mechanism (Wait-To-Restore) is used to prevent frequent recovery switching operations due to an intermittent defect (e.g. BER fluctuating around the SD threshold).

First, an LSP/span under failure condition must become fault-free, e.g. a BER less than a certain recovery threshold. After the recovered LSP/span (i.e. the previously working LSP/span) meets this criterion, a fixed period of time shall elapse before normal traffic uses the corresponding resources again. This duration called Wait-To-Restore (WTR) period or timer is generally of the order of a few minutes (for instance, 5 minutes) and should be capable of being set. The WTR timer may be either a fixed period, or provide for incrementally longer periods before retrying. An SF or SD condition on the previously working LSP/span will override the WTR timer value (i.e. the WTR cancels and the WTR timer will restart).

6.2 Revertive Mode Operation

In revertive mode of operation, when the recovery LSP/span is no longer required, i.e. the failed working LSP/span is no longer in SD or SF condition, a local Wait-to-Restore (WTR) state will be activated before switching the normal traffic back to the recovered working LSP/span.

During the reversion operation, since this state becomes the highest in priority, signalling must maintain the normal traffic on the recovery LSP/span from the previously failed working LSP/span. Moreover, during this WTR state, any null traffic or extra traffic (if applicable) request is rejected.

However, deactivation (cancellation) of the wait-to-restore timer may occur in case of higher priority request attempts. That is the recovery LSP/span usage by the normal traffic may be preempted if a higher priority request for this recovery LSP/span is attempted.

6.3 Orphans

When a reversion operation is requested normal traffic must be switched from the recovery to the recovered working LSP/span. A particular situation occurs when the previously working LSP/span cannot be recovered such that normal traffic can not be switched back. In such a case, the LSP/span under failure condition (also referred to as "orphan") must be cleared i.e. removed from the pool of resources allocated for normal traffic. Otherwise, potential de-synchronization between the control and transport plane resource usage can appear. Depending on the signalling protocol capabilities and behavior different mechanisms are expected here.

Therefore any reserved or allocated resources for the LSP/span under failure condition must be unreserved/de-allocated. Several ways can be used for that purpose: either wait for the elapsing of the clear-out time interval, or initiate a deletion from the ingress or the egress node, or trigger the initiation of deletion from an entity (such as an EMS or NMS) capable to react on the reception of an appropriate notification message.

7. Hierarchies

Recovery mechanisms are being made available at multiple (if not each) transport layers within so-called "IP/MPLS-over-optical" networks. However, each layer has certain recovery features and one needs to determine the exact impact of the interaction between the recovery mechanisms provided by these layers.

Hierarchies are used to build scalable complex systems. Abstraction is used as a mechanism to build large networks or as a technique for enforcing technology, topological or administrative boundaries by hiding the internal details. The same hierarchical concept can be applied to control the network survivability. Network survivability

is the set of capabilities that allow a network to restore affected traffic in the event of a failure. Network survivability is defined further in [TERM]. In general, it is expected that the recovery action is taken by the recoverable LSP/span closest to the failure in order to avoid the multiplication of recovery actions. Moreover, recovery hierarchies can be also bound to control plane logical partitions (e.g. administrative or topological boundaries). Each of them may apply different recovery mechanisms.

In brief, the commonly accepted ideas are generally that the lower layers can provide coarse but faster recovery while the higher layers can provide finer but slower recovery. Moreover, it is also desirable to avoid similar layers with functional overlaps to

optimize network resource utilization and processing overhead, since repeating the same capabilities at each layer does not create any added value for the network as a whole. In addition, even if a lower layer recovery mechanism is enabled, doing so does not prevent the additional provision of a recovery mechanism at the upper layer. The inverse statement does not necessarily hold; that is, enabling an upper layer recovery mechanism may prevent the use of a lower layer recovery mechanism. In this context, this section intends to analyze these hierarchical aspects including the physical (passive) layer(s).

7.1 Horizontal Hierarchy (Partitioning)

A horizontal hierarchy is defined when partitioning a single-layer network (and its control plane) into several recovery domains. Within a domain, the recovery scope may extend over a link (or span), LSP segment or even an end-to-end LSP. Moreover, an administrative domain may consist of a single recovery domain or can be partitioned into several smaller recovery domains. The operator can partition the network into recovery domains based on physical network topology, control plane capabilities or various traffic engineering constraints.

An example often addressed in the literature is the metro-core-metro application (sometimes extended to a metro-metro/core-core) within a single transport layer (see Section 7.2). For such a case, an end-to-end LSP is defined between the ingress and egress metro nodes, while LSP segments may be defined within the metro or core sub-networks. Each of these topological structures determines a so-called "recovery domain" since each of the LSPs they carry can have its own recovery type (or even scheme). The support of multiple recovery types and schemes within a sub-network is referred to as a

multi-recovery capable domain or simply multi-recovery domain.

7.2 Vertical Hierarchy (Layers)

It is a very challenging task to combine in a coordinated manner the different recovery capabilities available across the path (i.e. switching capable) and section layers to ensure that certain network survivability objectives are met for the different services supported by the network.

As a first analysis step, one can draw the following guidelines for a vertical coordination of the recovery mechanisms:
- The lower the layer the faster the notification and switching
- The higher the layer the finer the granularity of the recoverable entity and therefore the granularity of the recovery resource

Moreover, in the context of this analysis, a vertical hierarchy consists of multiple layered transport planes providing different:
- Discrete bandwidth granularities for non-packet LSPs such as OCh, ODUk, STS_SPE/HOVC and VT_SPE/LOVC LSPs and continuous bandwidth granularities for packet LSPs

- Potential recovery capabilities with different temporal granularities: ranging from milliseconds to tens of seconds

Note: based on the bandwidth granularity we can determine four classes of vertical hierarchies (1) packet over packet (2) packet over circuit (3) circuit over packet and (4) circuit over circuit. Below we briefly expand on (4) only. (2) is covered in [RFC3386]. (1) is extensively covered by the MPLS Working Group, and (3) by the PWE3 Working Group.

In SONET/SDH environments, one typically considers the VT_SPE/LOVC and STS SPE/HOVC as independent layers, VT_SPE/LOVC LSP using the underlying STS_SPE/HOVC LSPs as links, for instance. In OTN, the ODUk path layers will lie on the OCh path layer i.e. the ODUk LSPs using the underlying OCh LSPs as OTUk links. Note here that lower layer LSPs may simply be provisioned and not necessarily dynamically triggered or established (control driven approach). In this context, an LSP at the path layer (i.e. established using GMPLS signalling), for instance an optical channel LSP, appears at the OTUk layer as a link, controlled by a link management protocol such as LMP.

The first key issue with multi-layer recovery is that achieving individual or bulk LSP recovery will be as efficient as the underlying link (local span) recovery. In such a case, the span can be either protected or unprotected, but the LSP it carries must be

(at least locally) recoverable. Therefore, the span recovery process can be either independent when protected (or restorable), or triggered by the upper LSP recovery process. The former case requires coordination to achieve subsequent LSP recovery. Therefore, in order to achieve robustness and fast convergence, multi-layer recovery requires a fine-tuned coordination mechanism.

Moreover, in the absence of adequate recovery mechanism coordination (for instance, a pre-determined coordination when using a hold-off timer), a failure notification may propagate from one layer to the next one within a recovery hierarchy. This can cause "collisions" and trigger simultaneous recovery actions that may lead to race conditions and in turn, reduce the optimization of the resource utilization and/or generate global instabilities in the network (see [MANCHESTER]). Therefore, a consistent and efficient escalation strategy is needed to coordinate recovery across several layers.

Therefore, one can expect that the definition of the recovery mechanisms and protocol(s) is technology-independent such that they can be consistently implemented at different layers; this would in turn simplify their global coordination. Moreover, as mentioned in [RFC3386], some looser form of coordination and communication between (vertical) layers such a consistent hold-off timer configuration (and setup through signalling during the working LSP establishment) can be considered, allowing the synchronization between recovery actions performed across these layers.

7.2.1 Recovery Granularity

In most environments, the design of the network and the vertical distribution of the LSP bandwidth are such that the recovery granularity is finer at higher layers. The OTN and SONET/SDH layers can only recover the whole section or the individual connections it transports whereas the IP/MPLS control plane can recover individual packet LSPs or groups of packet LSPs and this independently of their granularity. On the other side, the recovery granularity at the sub-wavelength level (i.e. SONET/SDH) can be provided only when the network includes devices switching at the same granularity (and thus not with optical channel level). Therefore, the network layer can deliver control-plane driven recovery mechanisms on a per-LSP basis if and only if these LSPs have their corresponding switching granularity supported at the transport plane level.

7.3 Escalation Strategies

There are two types of escalation strategies (see [DEMEESTER]): bottom-up and top-down.

The bottom-up approach assumes that lower layer recovery types and schemes are more expedient and faster than the upper layer one. Therefore we can inhibit or hold-off higher layer recovery. However this assumption is not entirely true. Consider for instance a Sonet/SDH based protection mechanism (with a less than 50 ms protection switching time) lying on top of an OTN restoration mechanism (with a less than 200 ms restoration time). Therefore, this assumption should be (at least) clarified as: lower layer recovery mechanism is expected to be faster than upper level one if the same type of recovery mechanism is used at each layer.

Consequently, taking into account the recovery actions at the different layers in a bottom-up approach, if lower layer recovery mechanisms are provided and sequentially activated in conjunction with higher layer ones, the lower layers must have an opportunity to recover normal traffic before the higher layers do. However, if lower layer recovery is slower than higher layer recovery, the lower layer must either communicate the failure related information to the higher layer(s) (and allow it to perform recovery), or use a hold-off timer in order to temporarily set the higher layer recovery action in a "standby mode". Note that the a priori information exchange between layers concerning their efficiency is not within the current scope of this document. Nevertheless, the coordination functionality between layers must be configurable and tunable.

An example of coordination between the optical and packet layer control plane enables for instance the optical layer performing the failure management operations (in particular, failure detection and notification) while giving to the packet layer control plane the authority to decide and perform the recovery actions. In case the packet layer recovery action is unsuccessful, fallback at the optical layer can be subsequently performed.

The top-down approach attempts service recovery at the higher layers before invoking lower layer recovery. Higher layer recovery is service selective, and permits "per-CoS" or "per-connection" re-routing. With this approach, the most important aspect is that the upper layer should provide its own reliable and independent failure detection mechanism from the lower layer.

The same reference also suggests recovery mechanisms incorporating a coordinated effort shared by two adjacent layers with periodic

status updates. Moreover, some of these recovery operations can be pre-assigned (on a per-link basis) to a certain layer, e.g. a given link will be recovered at the packet layer while another will be recovered at the optical layer.

7.4 Disjointness

Having link and node diverse working and recovery LSPs/spans does not guarantee their complete disjointness. Due to the common physical layer topology (passive), additional hierarchical concepts such as the Shared Risk Link Group (SRLG) and mechanisms such as SRLG diverse path computation must be developed to provide complete working and recovery LSP/span disjointness (see [IPO-IMP] and [GMPLS-RTG]). Otherwise, a failure affecting the working LSP/span would also potentially affect the recovery LSP/span; one refers to such an event as "common failure".

7.4.1 SRLG Disjointness

A Shared Risk Link Group (SRLG) is defined as the set of links sharing a common risk (for instance, a common physical resource such as a fiber link or a fiber cable). For instance, a set of links L belongs to the same SRLG s, if they are provisioned over the same fiber link f.

The SRLG properties can be summarized as follows:

1) A link belongs to more than one SRLG if and only if it crosses one of the resources covered by each of them.

2) Two links belonging to the same SRLG can belong individually to (one or more) other SRLGs.

3) The SRLG set S of an LSP is defined as the union of the individual SRLG s of the individual links composing this LSP.

SRLG disjointness is also applicable to LSPs:

> The LSP SRLG disjointness concept is based on the following postulate: an LSP (i.e. sequence of links and nodes) covers an SRLG if and only if it crosses one of the links or nodes belonging to that SRLG.

> Therefore, the SRLG disjointness for LSPs can be defined as follows: two LSPs are disjoint with respect to an SRLG s if and only if they do not cover simultaneously this SRLG s.

Whilst the SRLG disjointness for LSPs with respect to a set S of SRLGs is defined as follows: two LSPs are disjoint with respect to a set of SRLGs S if and only if the common SRLGs between the sets of SRLGs they individually cover is disjoint from set S.

The impact on recovery is noticeable: SRLG disjointness is a necessary (but not a sufficient) condition to ensure network survivability. With respect to the physical network resources, a working-recovery LSP/span pair must be SRLG disjoint in case of dedicated recovery type. On the other hand, in case of shared recovery, a group of working LSP/span must be mutually SRLG-disjoint in order to allow for a (single and common) shared recovery LSP itself SRLG-disjoint from each of the working LSPs/spans.

8. Recovery Mechanisms Analysis

In order to provide a structured analysis of the recovery mechanisms detailed in the previous sections, the following dimensions can be considered:

1. Fast convergence (performance): provide a mechanism that aggregates multiple failures (this implies fast failure detection and correlation mechanisms) and fast recovery decision independently of the number of failures occurring in the optical network (implying also a fast failure notification).

2. Efficiency (scalability): minimize the switching time required for LSP/span recovery independently of the number of LSPs/spans being recovered (this implies an efficient failure correlation, a fast failure notification and time-efficient recovery mechanism(s)).

3. Robustness (availability): minimize the LSP/span downtime independently of the underlying topology of the transport plane (this implies a highly responsive recovery mechanism).

4. Resource optimization (optimality): minimize the resource capacity, including LSPs/spans and nodes (switching capacity), required for recovery purposes; this dimension can also be referred to as optimizing the sharing degree of the recovery resources.

5. Cost optimization: provide a cost-effective recovery type/scheme.

However, these dimensions are either outside the scope of this document such as cost optimization and recovery path computational aspects or mutually conflicting. For instance, it is obvious that providing a 1+1 LSP protection minimizes the LSP downtime (in case

of failure) while being non-scalable and consuming recovery resource without enabling any extra-traffic.

The following sections provide an analysis of the recovery phases and mechanisms detailed in the previous sections with respect to the dimensions described here above to assess the GMPLS protocol suite capabilities and applicability. In turn, this allows the evaluation of the potential need for further GMPLS signaling and routing extensions.

8.1 Fast Convergence (Detection/Correlation and Hold-off Time)

Fast convergence is related to the failure management operations. It refers to the elapsing time between the failure detection/ correlation and hold-off time, point at which the recovery switching actions are initiated. This point has been detailed in Section 4.

8.2 Efficiency (Recovery Switching Time)

In general, the more pre-assignment/pre-planning of the recovery LSP/span, the more rapid the recovery is. Since protection implies pre-assignment (and cross-connection) of the protection resources, in general, protection recover faster than restoration.

Span restoration is likely to be slower than most span protection types; however this greatly depends on the efficiency of the span restoration signalling. LSP restoration with pre-signaled and pre-selected recovery resources is likely to be faster than fully dynamic LSP restoration, especially because of the elimination of any potential crankback during the recovery LSP establishment.

If one excludes the crankback issue, the difference between dynamic and pre-planned restoration depends on the restoration path computation and selection time. Since computational considerations are outside the scope of this document, it is up to the vendor to determine the average and maximum path computation time in different scenarios and to the operator to decide whether or not dynamic restoration is advantageous over pre-planned schemes depending on the network environment. This difference depends also on the flexibility provided by pre-planned restoration versus dynamic restoration: the former implies a somewhat limited number of failure scenarios (that can be due, for instance, to local storage capacity limitation). The latter enables on-demand path computation based on the information received through failure notification message and as such is more robust with respect to the failure scenario scope.

Moreover, LSP segment restoration, in particular, dynamic restoration (i.e. no path pre-computation so none of the recovery

resource is pre-reserved) will generally be faster than end-to-end LSP restoration. However, local LSP restoration assumes that each LSP segment end-point has enough computational capacity to perform this operation while end-to-end LSP restoration requires only that LSP end-points provides this path computation capability.

Recovery time objectives for SONET/SDH protection switching (not including time to detect failure) are specified in [G.841] at 50 ms, taking into account constraints on distance, number of connections involved, and in the case of ring enhanced protection, number of nodes in the ring. Recovery time objectives for restoration mechanisms have been proposed through a separate effort [RFC3386].

8.3 Robustness

In general, the less pre-assignment (protection)/pre-planning (restoration) of the recovery LSP/span, the more robust the recovery type or scheme is to a variety of single failures, provided that adequate resources are available. Moreover, the pre-selection of the recovery resources gives in the case of multiple failure scenarios less flexibility than no recovery resource pre-selection. For instance, if failures occur that affect two LSPs sharing a common link along their restoration paths, then only one of these LSPs can be recovered. This occurs unless the restoration path of at least one of these LSPs is re-computed or the local resource assignment is modified on the fly.

In addition, recovery types and schemes with pre-planned recovery resources, in particular LSP/spans for protection and LSPs for restoration purposes, will not be able to recover from failures that simultaneously affect both the working and recovery LSP/span. Thus, the recovery resources should ideally be as disjoint as possible (with respect to link, node and SRLG) from the working ones, so that any single failure event will not affect both working and recovery LSP/span. In brief, working and recovery resource must be fully diverse in order to guarantee that a given failure will not affect simultaneously the working and the recovery LSP/span. Also, the risk of simultaneous failure of the working and the recovery LSP can be reduced. This, by computing a new recovery path whenever a failure occurs along one of the recovery LSPs or by computing a new recovery path and provision the corresponding LSP whenever a failure occurs along a working LSP/span. Both methods enable the network to maintain the number of available recovery path constant.

The robustness of a recovery scheme is also determined by the amount

of pre-reserved (i.e. signaled) recovery resources within a given shared resource pool: as the sharing degree of recovery resources increases, the recovery scheme becomes less robust to multiple LSP/span failure occurrences. Recovery schemes, in particular restoration, with pre-signaled resource reservation (with or without pre-selection) should be capable to reserve the adequate amount of resource to ensure recovery from any specific set of failure events, such as any single SRLG failure, any two SRLG failures etc.

8.4 Resource Optimization

It is commonly admitted that sharing recovery resources provides network resource optimization. Therefore, from a resource

utilization perspective, protection schemes are often classified with respect to their degree of sharing recovery resources with respect to the working entities. Moreover, non-permanent bridging protection types allow (under normal conditions) for extra-traffic over the recovery resources.

From this perspective 1) 1+1 LSP/Span protection is the most resource consuming protection type since not allowing for any extra-traffic 2) 1:1 LSP/span recovery requires dedicated recovery LSP/span allowing for extra-traffic 3) 1:N and M:N LSP/span recovery require 1 (M, respectively) recovery LSP/span (shared between the N working LSP/span) allowing for extra-traffic. Obviously, 1+1 protection precludes and 1:1 recovery does not allow for any recovery LSP/span sharing whereas 1:N and M:N recovery do allow sharing of 1 (M, respectively) recovery LSP/spans between N working LSP/spans. However, despite the fact that 1:1 LSP recovery precludes the sharing of the recovery LSP, the recovery schemes (see Section 5.4) that can be built from it (e.g. (1:1)^n) do allow sharing of its recovery resources. In addition, the flexibility in the usage of shared recovery resources (in particular, shared links) may be limited because of network topology restrictions, e.g. fixed ring topology for traditional enhanced protection schemes.

On the other hand, when using LSP restoration with pre-signaled resource reservation, the amount of reserved restoration capacity is determined by the local bandwidth reservation policies. In LSP restoration schemes with re-provisioning, a pool of spare resources can be defined from which all resources are selected after failure occurrence for the purpose of restoration path computation. The degree to which restoration schemes allow sharing amongst multiple independent failures is then directly inferred from the size of the resource pool. Moreover, in all restoration schemes, spare resources

can be used to carry preemptible traffic (thus over preemptible LSP/span) when the corresponding resources have not been committed for LSP/span recovery purposes.

From this, it clearly follows that less recovery resources (i.e. LSP/spans and switching capacity) have to be allocated to a shared recovery resource pool if a greater sharing degree is allowed. Thus, the network survivability level is determined by the policy that defines the amount of shared recovery resources and by the maximum sharing degree allowed for these recovery resources.

8.4.1. Recovery Resource Sharing

When recovery resources are shared over several LSP/Spans, the use of the Maximum Reservable Bandwidth, the Unreserved Bandwidth and the Maximum LSP Bandwidth (see [GMPLS-RTG]) provides the information needed to obtain the optimization of the network resources allocated for shared recovery purposes.

The Maximum Reservable Bandwidth is defined as the Maximum Link Bandwidth but it may be greater in case of link over-subscription.

The Unreserved Bandwidth (at priority p) is defined as the bandwidth not yet reserved on a given TE link (its initial value for each priority p corresponds to the Maximum Reservable Bandwidth). Last, the Maximum LSP Bandwidth (at priority p) is defined as the smaller of Unreserved Bandwidth (at priority p) and Maximum Link Bandwidth.

Here, one generally considers a recovery resource sharing degree (or ratio) to globally optimize the shared recovery resource usage. The distribution of the bandwidth utilization per TE link can be inferred from the per-priority bandwidth pre-allocation. By using the Maximum LSP Bandwidth and the Maximum Reservable Bandwidth, the amount of (over-provisioned) resources that can be used for shared recovery purposes is known from the IGP.

In order to analyze this behavior, we define the difference between the Maximum Reservable Bandwidth (in the present case, this value is greater than the Maximum Link Bandwidth) and the Maximum LSP Bandwidth per TE link i as the Maximum Shareable Bandwidth or max_R[i]. Within this quantity, the amount of bandwidth currently allocated for shared recovery per TE link i is defined as R[i]. Both quantities are expressed in terms of discrete bandwidth units (and thus, the Minimum LSP Bandwidth is of one bandwidth unit).

The knowledge of this information available per TE link can be exploited in order to optimize the usage of the resources allocated

per TE link for shared recovery. If one refers to r[i] as the actual bandwidth per TE link i (in terms of discrete bandwidth units) committed for shared recovery, then the following quantity must be maximized over the potential TE link candidates:

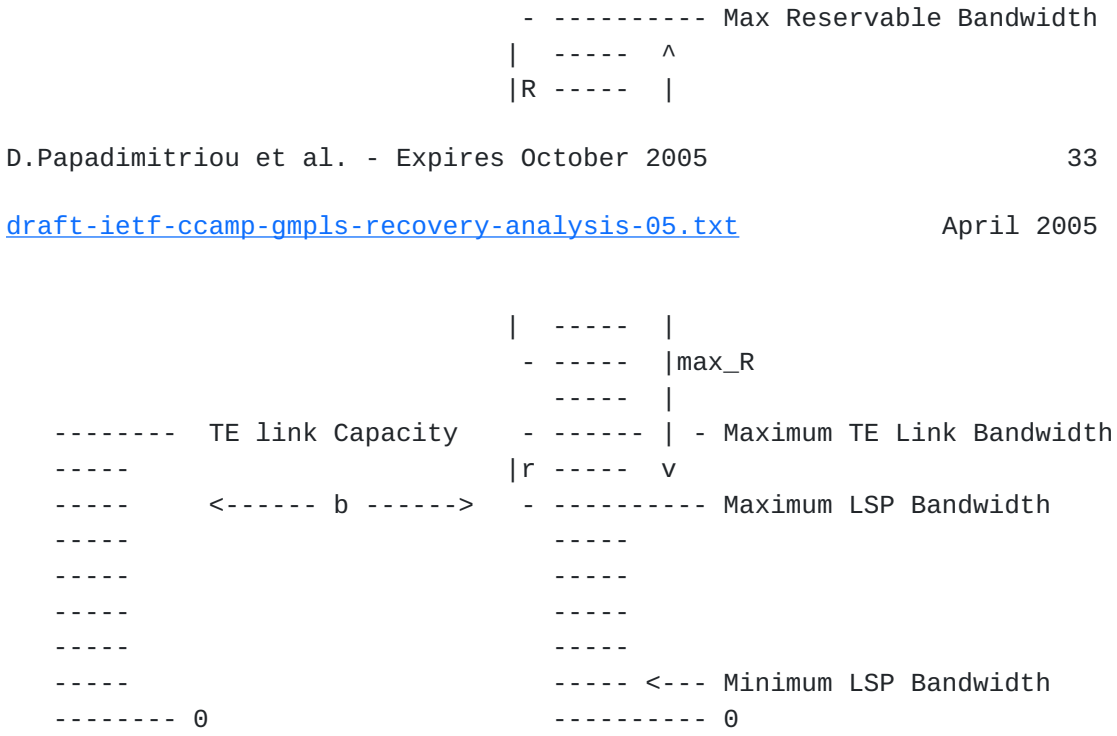
sum {i=1}^N [(R{i} - r{i})/(t{i} - b{i})]

or equivalently: sum {i=1}^N [(R{i} - r{i})/r{i}]

with R{i} >= 1 and r{i} >= 1 (in terms of per component bandwidth unit)

In this formula, N is the total number of links traversed by a given LSP, t[i] the Maximum Link Bandwidth per TE link i and b[i] the sum per TE link i of the bandwidth committed for working LSPs and other recovery LSPs (thus except "shared bandwidth" LSPs). The quantity [(R{i} - r{i})/r{i}] is defined as the Shared (Recovery) Bandwidth Ratio per TE link i. In addition, TE links for which R[i] reaches max_R[i] or for which r[i] = 0 are pruned during shared recovery path computation as well as TE links for which max_R[i] = r[i] which can simply not be shared.

More generally, one can draw the following mapping between the available bandwidth at the transport and control plane level:



Note that the above approach does not require the flooding of any per LSP information or any detailed distribution of the bandwidth allocation per component link or individual ports or even any per-priority shareable recovery bandwidth information (using a dedicated

sub-TLV). The latter would provide the same capability than the already defined Maximum LSP bandwidth per-priority information. Such approach is referred to as a Partial (or Aggregated) Information Routing as described for instance in [KODIALAM1] and [KODIALAM2]. They show that the difference obtained with a Full (or Complete) Information Routing approach (where for the whole set of working and recovery LSPs, the amount of bandwidth units they use per-link is known at each node and for each link) is clearly negligible. The latter approach is detailed in [GLI], for instance. Note also that both approaches rely on the deterministic knowledge (at different degrees) of the network topology and resource usage status.

Moreover, extending the GMPLS signalling capabilities can enhance the Partial Information Routing approach. This, by allowing working LSP related information and in particular, its path (including link and node identifiers) to be exchanged with the recovery LSP request to enable more efficient admission control at upstream nodes of shared recovery resources, in particular links (see Section 8.4.3).

8.4.2 Recovery Resource Sharing and SRLG Recovery

Resource shareability can also be maximized with respect to the number of times each SRLG is protected by a recovery resource (in particular, a shared TE link) and methods can be considered for avoiding contention of the shared recovery resources in case of single SRLG failure. These methods enable for the sharing of recovery resources between two (or more) recovery LSPs if their respective working LSPs are mutually disjoint with respect to link, node and SRLGs. A single failure then does not simultaneously disrupt several (or at least two) working LSPs.

For instance, [BOUILLET] shows that the Partial Information Routing approach can be extended to cover recovery resource shareability with respect to SRLG recoverability (i.e. the number of times each SRLG is recoverable). By flooding this aggregated information per TE

link, path computation and selection of SRLG-diverse recovery LSPs can be optimized with respect to the sharing of recovery resource reserved on each TE link giving a performance difference of less than 5% (and so negligible) compared to the corresponding Full Information Flooding approach (see [GLI]).

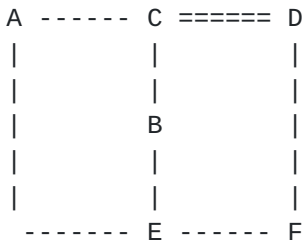
For this purpose, additional extensions to [GMPLS-RTG] in support of path computation for shared mesh recovery have been often considered in the literature. TE link attributes would include, among other, the current number of recovery LSPs sharing the recovery resources

reserved on the TE link and the current number of SRLGs recoverable by this amount of (shared) recovery resources reserved on the TE link. The latter is equivalent to the current number of SRLGs that the recovery LSPs sharing the recovery resource reserved on the TE link shall recover. Then, if explicit SRLG recoverability is considered an additional TE link attribute including the explicit list of SRLGs recoverable by the shared recovery resource reserved on the TE link and their respective shareable recovery bandwidth. The latter information is equivalent to the shareable recovery bandwidth per SRLG (or per group of SRLGs) which implies to consider a decreasing amount of shareable bandwidth and SRLG list over time.

Compared to the case of recovery resource sharing only (regardless of SRLG recoverability, as described in Section 8.4.1), this additional TE link attributes would potentially deliver better path computation and selection (at distinct ingress node) for shared mesh recovery purposes. However, due to the lack of results of evidence for better efficiency and due to the complexity that such extensions would generate, they are not further considered in the scope of the present analysis. For instance, a per-SRLG group minimum/maximum shareable recovery bandwidth is restricted by the length that the corresponding (sub-)TLV may take and thus the number of SRLGs that it can include. Therefore, the corresponding parameter should not be translated into GMPLS routing (or even signalling) protocol extensions in the form of TE link sub-TLV.

8.4.3 Recovery Resource Sharing, SRLG Disjointness and Admission Control

Admission control is a strict requirement to be fulfilled by nodes giving access to shared links. This can be illustrated using the following network topology:



Node A creates a working LSP to D (A-C-D), B creates simultaneously a working LSP to D (B-C-D) and a recovery LSP (B-E-F-D) to the same

destination. Then, A decides to create a recovery LSP to D (A-E-F-D), but since the C-D span carries both working LSPs, node E should

either assign a dedicated resource for this recovery LSP or reject this request if the C-D span has already reached its maximum recovery bandwidth sharing ratio. Otherwise, in the latter case, C-D span failure would imply that one of the working LSP would not be recoverable.

Consequently, node E must have the required information to perform admission control for the recovery LSP requests it processes (implying for instance, that the path followed by the working LSP is carried with the corresponding recovery LSP request). If node E can guarantee that the working LSPs (A-C-D and B-C-D) are SRLG disjoint over the C-D span, it may securely accept the incoming recovery LSP request and assign to the recovery LSPs (A-E-F-D and B-E-F-D) the same resources on the link E-F. This, if the link E-F has not yet reached its maximum recovery bandwidth sharing ratio. In this example, one assumes that the node failure probability is negligible compared to the link failure probability.

To achieve this, the path followed by the working LSP is transported with the recovery LSP request and examined at each upstream node of potentially shareable links. Admission control is performed using the interface identifiers (included in the path) to retrieve in the TE DataBase the list of SRLG Ids associated to each of the working LSP links. If the working LSPs (A-C-D and B-C-D) have one or more link or SRLG id in common (in this example, one or more SRLG id in common over the span C-D) node E should not assign the same resource over link E-F to the recovery LSPs (A-E-F-D and B-E-F-D). Otherwise, one of these working LSPs would not be recoverable in case of C-D span failure.

There are some issues related to this method, the major one being the number of SRLG Ids that a single link can cover (more than 100, in complex environments). Moreover, when using link bundles, this approach may generate the rejection of some recovery LSP requests. This occurs when the SRLG sub-TLV corresponding to a link bundle includes the union of the SRLG id list of all the component links belonging to this bundle (see [GMPLS-RTG] and [BUNDLE]).

In order to overcome this specific issue, an additional mechanism may consist of querying the nodes where such an information would be available (in this case, node E would query C). The main drawback of this method is that, in addition to the dedicated mechanism(s) it requires, it may become complex when several common nodes are traversed by the working LSPs. Therefore, when using link bundles, solving this issue is tightly related to the sequence of the recovery operations. Per component flooding of SRLG identifiers would deeply impact the scalability of the link state routing protocol. Therefore, one may rely on the usage of an on-line accessible network management system.

9. Summary and Conclusions

The following table summarizes the different recovery types and schemes analyzed throughout this document.

		Path Search (computation and selection)	
		Pre-planned (a)	Dynamic (b)
Path Setup	1	faster recovery less flexible less robust most resource consuming	Does not apply
	2	relatively fast recovery relatively flexible relatively robust resource consumption depends on sharing degree	Does not apply
	3	relatively fast recovery more flexible relatively robust less resource consuming depends on sharing degree	less faster (computation) most flexible most robust least resource consuming

1a. Recovery LSP setup (before failure occurrence) with resource reservation (i.e. signalling) and selection is referred to as LSP protection.

2a. Recovery LSP setup (before failure occurrence) with resource reservation (i.e. signalling) and with resource pre-selection is referred to as pre-planned LSP re-routing with resource pre-selection. This implies only recovery LSP activation after failure occurrence.

3a. Recovery LSP setup (before failure occurrence) with resource reservation (i.e. signalling) and without resource selection is referred to as pre-planned LSP re-routing without resource pre-selection. This implies recovery LSP activation and resource (i.e. label) selection after failure occurrence.

3b. Recovery LSP setup after failure occurrence is referred to as

to as LSP re-routing, which is full when recovery LSP path computation occurs after failure occurrence.

The term pre-planned refers thus to recovery LSP path pre-computation, signaling (reservation), and a priori resource selection (optional), but not cross-connection. Also, the shared-

mesh recovery scheme can be viewed as a particular case of 2a) and 3a) using the additional constraint described in Section 8.4.3.

The implementation of these recovery mechanisms requires only considering extensions to GMPLS signalling protocols (i.e. [RFC3471] and [RFC3473]). These GMPLS signalling extensions should mainly focus in delivering (1) recovery LSP pre-provisioning for the cases 1a, 2a and 3a, (2) LSP failure notification, (3) recovery LSP switching action(s), and (4) reversion mechanisms.

Moreover, the present analysis (see Section 8) shows that no GMPLS routing extensions are expected to efficiently implement any of these recovery types and schemes.

10. Security Considerations

This document does not introduce any additional security issue or imply any specific security consideration from [RFC3945] to the current RSVP-TE GMPLS signaling, routing protocols (OSPF-TE, IS-IS-TE) or network management protocols.

However, the authorization of requests for resources by GMPLS-capable nodes should determining whether a given party, presumable already authenticated, has a right to access the requested resources. This determination is typically a matter of local policy control, for example by setting limits on the total bandwidth made available to some party in the presence of resource contention. Such policies may become quite complex as the number of users, types of resources and sophistication of authorization rules increases. This is particularly the case for recovery schemes that assume pre-planned sharing of recovery resources, or contention for resources in case of dynamic re-routing.

Therefore, control elements should match them against the local authorization policy. These control elements must be capable of making decisions based on the identity of the requester, as verified cryptographically and/or topologically.

11. IANA Considerations

This document defines no new code points and requires no action by IANA.

12. Acknowledgments

The authors would like to thank Fabrice Poppe (Alcatel) and Bart Rousseau (Alcatel) for their revision effort, Richard Rabbat (Fujitsu Labs), David Griffith (NIST) and Lyndon Ong (Ciena) for their useful comments.

Thanks also to Adrian Farrel for the thorough review of the document.

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Funding for the RFC Editor function is currently provided by the Internet Society.