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TITLE:

Inference of Shared Risk Link Groups

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ABSTRACT: The Shared Risk Link Group (SRLG) concept introduced in [IPO-Frame] is considered as one of the most important criteria concerning the constrained-based path computation of optical channel routes. By applying the SRLG constraint criteria to the constrained-based path computation, one can select a route taking into account resource and logical structure disjointness that implies a lower probability of simultaneous lightpath failure. This contribution describes the various physical and logical resource types considered in the SRLG concept. The proposed model focuses on the inference of SRLG information between the network physical layers as well as logical structures such as geographical locations. The main applications of the proposed model are related to the Constraint-based Shortest Path First (CSPF) algorithm for optical channel route computation and the aggregation of the SRLG information flooded throughout traffic engineering extensions of the IGP routing protocols (such as OSPF and IS-IS).

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1. Introduction

Many proposals include the SRLG concept when considering the disjointness of the constraint-based path computation for optical channel routes. In optical domains this concept of SRLG is used for deriving a path, which is disjoint from the physical resource and logical topology point-of-view. The SRLG concept and the corresponding requirements have already been described in [IPO-OLCP] while considering physical network topology and associated risks. Within the scope of this document, these requirements can be summarized as follows:

1. The SRLG encoding mechanism should reduce the path computation complexity.

2. The SRLG information flooding should be scoped to reduce the amount of information that is sent across domains.

3. The SRLG encoding should accommodate the physical and logical restrictions imposed on the diversity requirements.

However, the definition of SRLG in the current format as described in [GMPLS-OSPF] and [GMPLS-ISIS] does not provide:

1. The relationship between logical structures or physical resources. For example, a fiber could be part of a sequence of fiber segments, which is included in a given geographical region

2. The risk assessment during path computation implying the allocation of a conditional failure probabilities with the SRLGs

3. The analysis of the specifications of constraint-based path computation and path re-optimization taking SRLG information into account.

The model described in this document proposes a technique to compute the SRLG with respect to a given risk type. This is achieved by identifying for a given physical layer the resources belonging to an SRLG. The proposed model also permits to compute the dependencies of these resources on the resources belonging to lower physical layers. The result of the computation also enables to determine the risk associated to each of the SRLGs.

The remainder of this memo is organized as follows. In section 3, we present the hierarchical model of the resources and the corresponding SRLG encoding. In section 4, we discuss the use of such a model for the risk assessment for the path computation. Future work is proposed in section 5, which is followed by references in section 6. Appendix 1 provides an elaborate discussion on the inference of SRLGs.

2. Relationship between SRLG and SRG Concepts

However, as stated in [CCAMP-SRG] risk sharing is not limited to links. This reference extends the applicability of SRLGs to path (or connections) included in a *domain*, where we define a *domain* to be a group of resources (nodes and links) that provide similar capabilities and that share the same set of risk(s).

Note that in such a scenario (for example in ring topology), a failure will affect all the other resources in the domain. This observation parallels the notion of what SRLG means for a link to what an SRG (Shared Risk Group) means for a domain. One can visualize the capabilities of a domain to be defined as the same protection capabilities, the same link encoding type, same multiplexing capability, same resource class and same Traffic-Engineering Metric etc.

The “shared risk concept” can also be viewed as a mechanism to hide or reduce the amount of topology information propagated in a multi-layered network. Consider a multi-layered network with fiber, optical (for instance G.709 OTN), SONET/SDH and router topology in the ascending order of encompassing the previous topology. Here the upper layer (which encompasses the lower layers) is called the client layer and the lower layer is called the server layer. In such a topology a link at the client layer (for example, router level) can mean many nodes and links in the server layer (for example, SONET/SDH, optical and fiber level). Hence to provide diversity at the client layer link level one should consider failures in the server layer topology. Thus, to provide diverse links or paths (sequences of links) at the client layer requires some means of abstracting the diversity at the server layer, so that this abstraction can be used by path computation at the client layer.

At present the only way to provide this abstraction of the server layer topology in the client layers is to use the SRLG concept. With the adoption of Generalized MPLS (GMPLS) control plane in the packet and circuit based networks it is possible to compute diverse paths through multiple layers. The notion of diversity can be abstracted and dynamically computed at many layers. [CCAMP-SRG] concentrates on the risk associated with a sequence of disjoint elements (unlike in case of SRLG) and the procedures of doing such a task.

3. Hierarchical Model

The model described in this proposal includes two hierarchies defined as follows:

- Physical hierarchy, which is related to the fiber topology (more generally the physical resources) of the optical network including the wavelengths built on top of this physical topology.

- Logical hierarchy, which is related to the geographical topology of the network.

Between these two hierarchies, the nodes such as Optical Cross-Connect (OXC) and Photonic Cross-Connect (PXC) constitute the boundary layer. Each of these concepts is elaborated in the following sections.

The encoding of the SRLG could be either mapped on this hierarchical model or simply use a flat encoding scheme. Both methods seam feasible. Difference between both approaches relies on the extended usage of the SRLGs in the context of diverse route computation (i.e. path disjointness). Since a link can belong to more than one SRLG, an SRLG identifier list (i.e. the SRLG Sub-TLV), as described in [GMPLS-OSPF] and [GMPLS-ISIS] is associated with the link to which this link belongs (i.e. the SRLG Sub-TLV is defined as a Sub-TLV of the Link TLV). This results in a linear, unordered and non-structured information from which the underlying structure cannot be deduced.

Consequently, either a type field indicating the type of resource (or logical structure) to which this SRLG identifier refers extends the flat encoding scheme or the encoding itself translates the underlying hierarchical structure. Worth mentioning here that an hierarchical encoding (since depending on the physical layer which is by definition static) needs an additional mapping structure in order to keep the relationship with link identifiers. Nevertheless, the computational model developed in Appendix 1 does not depend on the encoding scheme.

3.1 Physical Hierarchy (or Network Resource Hierarchy)

The network (physical) resource model considered in the inference of the Shared Risk Link Groups (SRLGs) is based on concepts detailed in [IPO-FRAME] and [IPO-OLCP]. The concepts around network resource hierarchy developed within this document are based on the following definitions:

- Sub-Channel: a dedicated container included within a given channel uniquely identifies a sub-channel
- Channel (or wavelength): a channel is uniquely identified by a dedicated wavelength (i.e. lambda)
- Fiber Link: a fiber connects two node ports communicating through one optical channel or more than one optical channel if the node interfaces support Wavelength Division Multiplexing (WDM).
- Fiber Sub-segment: grouping of several fiber links forms a fiber sub-segment.
- Fiber Segment: a fiber segment includes a collection of fiber sub- segments.
- Fiber Trunks: a fiber trunk is a sequence of fiber segments, including one or more fiber segments starting and terminating at the same node.

The model developed extends the definition given within [IPO-OLCP] and [IPO-FRAME] by enabling ‘fiber topology’ non-limited to point-to-point node connections. Physical resources considered within this model are a common denominator of most Optical Transport Network (OTN) environments.

As represented in Figure 1, the fiber trunk from the location N1 to the location N3 is composed by the fiber segments A and B and the fiber trunk from the location N1 to the location N2 includes the fiber segment A, C and D.

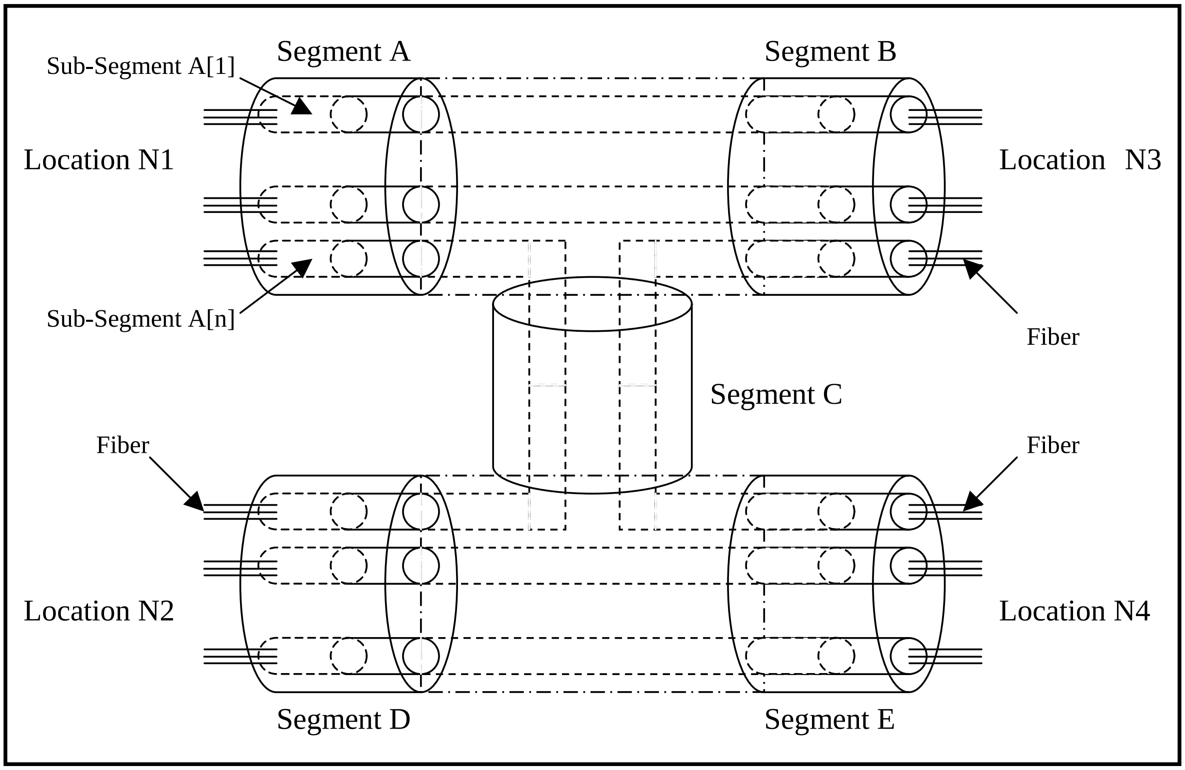


Figure 1. Example of Network Physical Topology

In this figure, the Segment A is composed by the fiber sub-segments A[1], A[2], ..., A[I], ..., A[n]. The same terminology applies for the segments B, C, D and E.

Consequently, the fiber trunk from location N2 to location N4 includes the sub-segments D[2] to D[n] and their corresponding sub-segments within the segment E: E[2] to E[n]. The fiber trunk from location N1 to location N2 includes the fiber sub-segments A[n], C[1] and D[1].

3.2 Geographical Hierarchy (or Logical Structure Hierarchy)

Concerning the geographical hierarchy, the SRLG model developed in this document, includes the following definitions going from the less to the most extended logical structure partitioning of the area covered by the optical network (as shown in Figure 2.)

- Node: a node is a single device or active element included within the optical network; a node could be an Optical Cross-Connect (OXC) or a Photonic Cross-Connect (PXC). Exit points of a node are defined as the node ports.

- Zone: a zone includes one or more nodes whose location is limited to a confined area for the sake of maintainability. Zones have a fixed number of exit points and are non-overlapping meaning that a given node belongs to only one zone.

– Region: a region includes one or more zones whose location covers the individual locations of each of the area composing this region. Regions have a fixed number of exit points and are non- overlapping meaning that a given zone belongs to only one region.

Hence, a region could include one or more than one non-overlapping zone each of these zones could include one or generally more than one node.

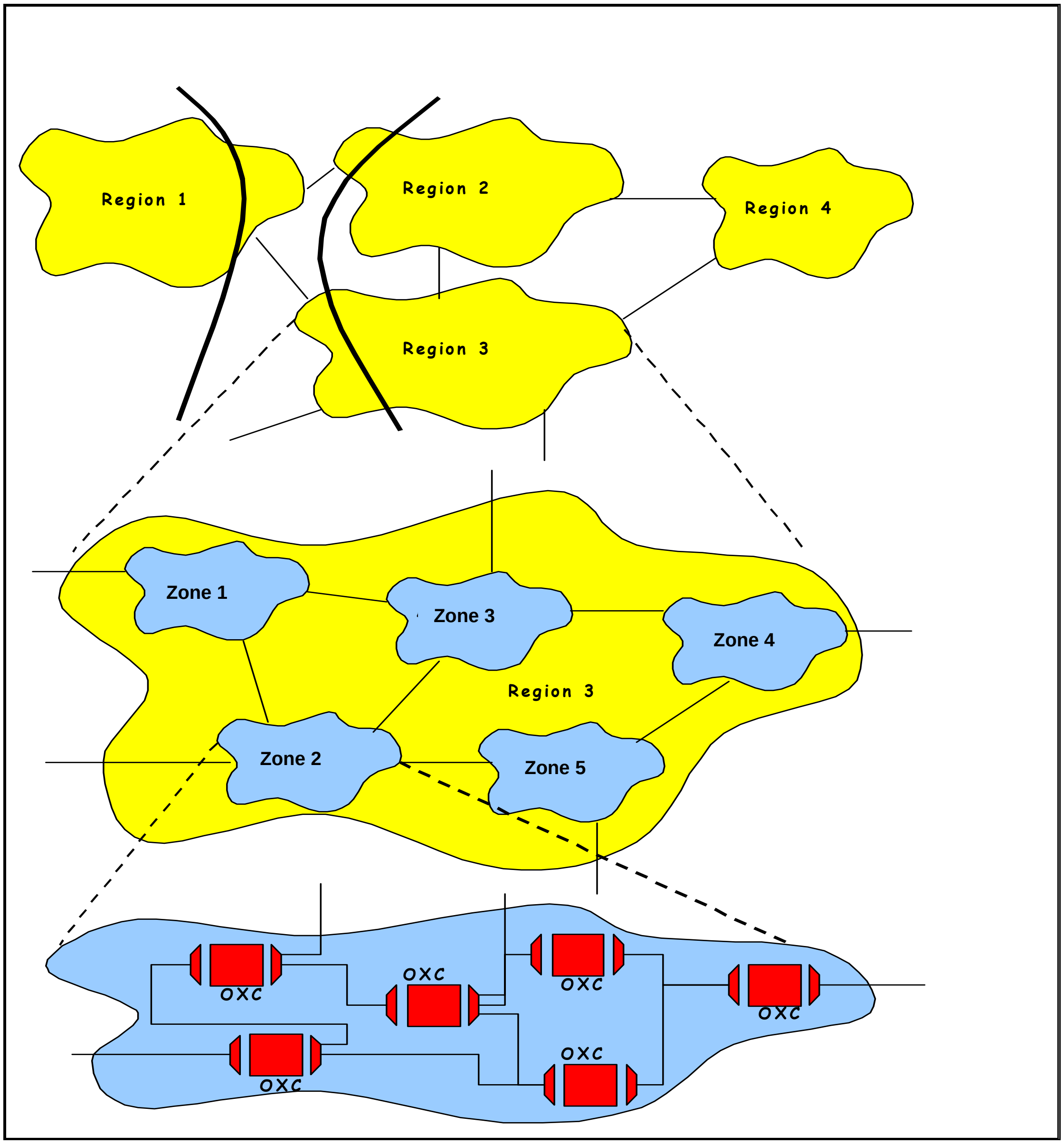


Figure 2. Example of Hierarchical Topology (Logical Structure)

Note: A zone could correspond to an IGP area such as an OSPF area, and a region to an OSPF Autonomous System (or BGP Autonomous Systems). However, the model does not exclude network topologies where the SRLG geographical hierarchy does not map the routing hierarchical topology.

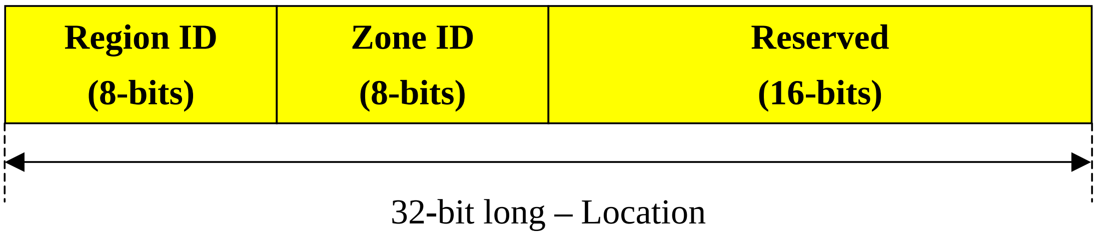
3.3 Hierarchical SRLG encoding

The objective of the hierarchical encoding is to achieve aggregation (i.e. summarization) of the SRLG Identifiers at the boundary of geographical structures defined logically on top of the optical network topology. For this purpose, we propose a linear encoding scheme including a type field. This provides abstraction of the physical layer structure and should facilitate the management of the SRLG Identifiers.

Consequently, the detailed encoding of an SRLG includes:

1. SRLG Location (32-bit field)

The encoding of the SRLG Location is defined as:

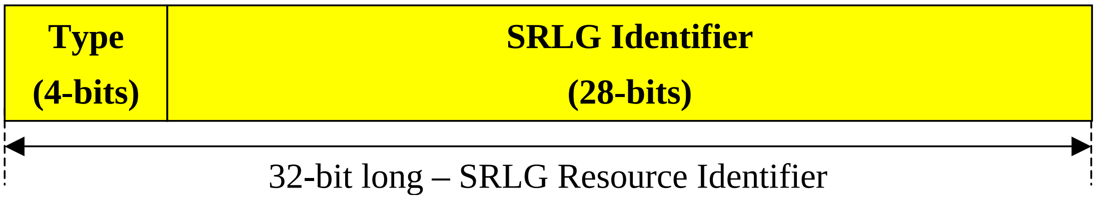


The SRLG Location field identifies the logical structure into which the common resource(s) defining the SRLG are included. For simplicity, we say that the SRLG Location field identifies the location of the SRLG.

The Location field includes the Region ID (8-bit) which identifies a Region and the Zone ID (8-bit) identifying a Zone belonging to this Region.

2. SRLG Resource Identifier (32-bit field)

The encoding of the SRLG Resource Identifier is defined as:



Within the SRLG Resource Identifier, the Type field (4-bit integer) defines the resource type (i.e. the “link” type) of the SRLG Identifier defined as a 28-bit integer value. The following resource types (i.e. “link” type) are currently defined:

Type	**Value (oct)**
Reserved	0x00
Fiber Trunk	0x01
Fiber Segment	0x02
Fiber Sub-segment	0x03
Fiber Link	0x04

Logical resources such as optical channels and TDM circuits or optical sub-channels can be also defined as described in Section 3 (notice that logical resource doesn’t correspond to logical structures since the latter refers to the geographical hierarchy and not to the network resource hierarchy):

Type	**Value (oct)**
Optical Channel	0x05
Optical Sub-Channel	0x06

Since a given resource (for instance a fiber link) can belong to more than one SRLG, the SRLG Identifier structure is defined in the most general case as a list of SRLG Identifiers (n x 32-bit):

Type (4-bits)	SRLG Identifier #1 (28-bits)
Type (4-bits)	SRLG Identifier #2 (28-bits)
Type (4-bits)	SRLG Identifier #N (28-bits)

Therefore, though we propose a linear encoding, the summarization of the SRLG (at the logical structure boundaries) is still possible since the SRLG identifiers are structured as follows:

- An SRLG Location field (32 bits): Region (8 bits) + Zone (8 bits) + Unspecified (16 bits)
- An SRLG Identifier field (32 bits): Type (4 bits) + Identifier (28 bits)

This encoding enables one to perform summarization at the boundaries of logical structures defining the spatial coverage of an SRLG Identifier List while overcoming the drawbacks of full hierarchical encoding scheme.

Note: the proposed encoding does not include the conditional failure probability as defined in section 4.2

4. Risk Assessment

Risk assessment is defined as the quantification process of the potential risk associated to the inclusion of a given resource (this resource belongs to a given resource type located within a given logical structure such as a geographical location) in a given optical channel.

4.1 Rationale for Risk Assessment

Consider the following example, where the client device makes the following connection requests to the optical network:

- Request for a persistent connection with 99.999 % (well known 5 9s) of availability or equally a down time less than X minutes per year.

- Request a high-protection for a portion of the traffic (at the expense of more charging) compared to other low-priority traffic.

Such requirements will be translated into path specific request. Such path specific request can be grouped into path selection requirements and path characterization requirements.

1. <u>Path selection requirements</u>

These typically dictate which physical path should be taken to achieve the availability requirements of the client. These requirements are typically the logical and physical diversity as mentioned in the hierarchical encoding section (see section 3).

2. <u>Path characterization requirements</u>

Path characterization requirements typically dictate the protection mechanisms as specified by the client connection request. This can be achieved in the form of optical ringed protection, meshed protection mechanisms, or combination of both linear and ringed protection. However, these are out of the scope of this document.

The components that need formalization in this example are:

- Step 1. Specification of the user requirements (such as the example above)
- Step 2. Configuring the network that helps in assessing the features such as the availability
- Step 3. Propagating the above-configured information.
- Step 4. Using the above-propagated information.

Step 1 of specifying the requirements is not in the scope of this document. Steps 2 to 4 are discussed in the remainder of this document.

As an example for this discussion we elaborate on the risk assessment for a selected path.

4.2 Quantifying the Risk Assessment

Risk (the complementary of availability) assessment is defined as the evaluation of the potential risk associated to the inclusion of a specific resource (this resource belongs to a given resource type located within a given logical structure such as a geographical location) in a given path.

Given that an SRLG Identifier list is used to encode the group of logical or physical resources, if a mechanism is devised to assign the risk associated with the corresponding resource, we can calculate the availability of the corresponding path. This, in order to meet the connection availability as requested by the client.

A simple approach is to assign the conditional failure probability with each of the SRLG Identifier. This information can be encoded as an optional parameter along with the SRLG information as defined in Section 3.3. In addition, weights can be associated to each of the SRLG to either increase or decrease the potential usage of the resource (i.e. inclusion into the selected route).

In this approach the configurable parameters are:

- SRLG Resource and SRLG Location Identifiers
- Conditional failure probability per SRLG
- Weight for the selection of the SRLG

As mentioned above, the resource failure probability is defined as a conditional probability. For instance, we can associate a conditional failure probability of 25% to any fiber sub-segment located within the same zone. It means that by selecting two (or more than two) different optical channel routes including the same SRLG identifier with respect to fiber sub-segment failure, if one of these lightpaths fails, then the probability that the other lightpath fails is 25%.

Moreover, the failure probability of a fiber can also depend on the zone into which the fiber is located as well as the length of the fiber. In addition, a fiber can pass across different zones with different failure probabilities. In this case, we need to consider an aggregated failure probability per fiber taking into account each of the failure probability of the sub-components.

For instance, if we refer to our previous example and by considering that:

1. a conditional failure probability of 50% is associated to any fiber link
2. a conditional failure probability of 1% to any fiber segment located within the same zone

Then by selecting two different optical channels included within the same SRLG with respect to fiber segment failure (S1, for instance), we obtain a simultaneous lightpath failure probability of 1%. Consequently, if the client asks for a protected path, by choosing fiber segment path disjointness, the simultaneous lightpath failure probability is also of 1%. However, choose two optical channels flowing through the same fiber (r1, for instance), then we have a probability of 50% that both optical channels fail simultaneously.

4.3 Risk Assessment Application

Up to now we didn’t define the association between the high availability of the path and SRLG conditional failure probability. A simple way to define the relationship is to consider the availability of the service requested by the client (i.e. a working and a protected path from the provider point of view) and conditional failure probability of the sequence of physical resource elements included within the corresponding paths. So if we consider:

1. a path whose source is located is zone 1 and whose destination in zone 2 (same region)
2. a conditional failure probability of 1% if fiber links are selected within the same fiber trunk (and located within the zone 1)
3. a conditional failure probability of 1% if fiber links are selected within the same fiber trunk (and located within the zone 2)
4. the conditional failure probabilities are independent and weighted equally

Then, the availability of the service concerning the fiber link availability is of 98% since in this specific case conditional failure probabilities are additive.

Note that currently, the initial conditional failure probability value need to be statically encoded; however, based on the "history" of the failures these values could be dynamically re-evaluated. The corresponding mechanism still needs to be specified and left for further study.

5. SRLG Inference Model Application

The SRLG Inference Model applications are related to the CSPF lightpath route computation and the SRLG Identifier sets summarization in order to enable intra- and inter-area diverse routing. For that purpose we first extend the SRLG concept for logical resources such as optical channels and optical sub-channels (i.e. TDM circuits).

5.1 Extension of the SRLG Concept to Logical Structures and Resources

The SRLG concept can be extended to logical-level structures and resources by taking into account the following purposes:

1. Given the physical and geographical-level decomposition of the optical network topology, the SRLG encoding can be hierarchically structured. The hierarchical encoding helps in constructing the logical-level topological abstraction, which in turn can be used in the SRLG summarization and loose-path computation. The link semantics could be also extended to accommodate the inter-region and inter-zonal links.
2. Propagate these additional logical-level (structures and resources) links using the IGP routing protocols for intra- and inter-area routing purposes.
3. To reduce the amount of the flooded information and hence lightpath route computation complexity, the flooding scope of the information propagation is extended to accommodate logical structures (i.e. region and zone) and logical resources (i.e. optical channels and TDM circuits).

5.2 Propagation SRLG Information

The SRLG of each link (i.e. physical and logical resources) is encoded as described in Section 3.3, and this information is propagated once at configuration between the various nodes using the traffic engineering extensions to the IGP routing protocols such as OSPF [GMPLS-OSPF] and IS-IS [GMPLS-ISIS]. After this initial SRLG identifier exchange, corresponding values do not change over the time.

This propagation of SRLG information will be necessary whenever a new link is added or an existing link is removed. Initially the probability of failure of the various resources are assumed to be configured; it is envisioned that at some later time, the probability of failure of the SRLG will be propagated along with the SRLG itself (as described in Section 3.3).

5.3 Bottom-Up Computation of the SRR Relations

Once the traffic-engineering topological information is received by the node, the Shared Risk Relationship (SRR) graph can be calculated on a regular basis, using the bottom up method described in Appendix 1. The fiber trunk SRR is used to compute the fiber segment SRR, which in turn is then used to compute the fiber sub-segment SRR until the fiber SRR computation is achieved. To the SRR which defines the membership of a resource belonging to the same SRLG set, we associate at each resource level (for instance, with this fiber SRR), the conditional failure probability between two elements belonging to this level (for instance, between two fibers).

5.4 Summarization in Topology and Resource Distribution

By combining recursively several dependency graphs of known structures into a higher-level dependency graph, the number of SRLG sets and the number of element they include can be further reduced (i.e. the SRLG identifier information is aggregated). Consequently, the applications of the extended model will also cover the reduction of the SRLG advertisements in the Topology and Resource Distribution running instance (i.e. the traffic engineering extensions to the link-state advertisements of the IGP protocol). In turn, this improvement will reduce the CSPF algorithm complexity for optical channel path calculation (i.e. engineered lightpath setup).

5.5 CSPF Route Computation

Applications of this model are directly related to the Constraint-based Shortest Path First (CSPF) algorithm used for lightpath route computation (i.e. traffic-engineered lightpath creation) to maximize the lightpath disjointness and so decrease their common failure probability. Given an existing set of lightpaths across the network, the objective is thus to compute a route across the optical network topology for a newly requested lightpath such that this lightpath is diversely routed from a given set of existing lightpaths.

The diversity requirement is a routing constraint, and is expressed as the conditional failure probability of a requested lightpath with respect to the failure of an existing (set of) lightpath. Hence, in addition to the other traffic-engineering constraints, the diversity constraint requires that the conditional failure probability not exceed a given threshold. Therefore, the CSPF algorithm needs to be updated to take the routing diversity constraint into account.

Moreover, the SRLG concept generates another dimension to the existing constraint-based path computation methods traditionally used in MPLS (or PNNI) based hierarchical networks. The SRLG constraints provide an additional dimension to the common traffic-engineering constraints such as bandwidth availability, link metrics and other parameters. The routing diversity constraint specificity requires the use of more appropriate path computation algorithms that provide not only complete multi-path disjointness but also partial multi-path disjointness with respect to various risk factors. In a similar way, appropriate mechanisms should also be used in order to perform path re-optimization following various restoration strategies.

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Appendix 1: Inference of SRLG Model

1.1 Definition of the Concept

The present model is intended to be used to automate the discovery of the Shared Risk Link Groups (SRLGs) at a given layer for a given physical resource type. This resource type could be located within a given region and zone. A typical resource type will be a fiber, a fiber sub-segment, a fiber segment or a fiber trunk and a typical resource location can be a zone, a region or a node. Moreover, For a given resource type, when the resource location is not specified, the resource location is limited to the node(s) which advertising the corresponding SRLG identifiers.

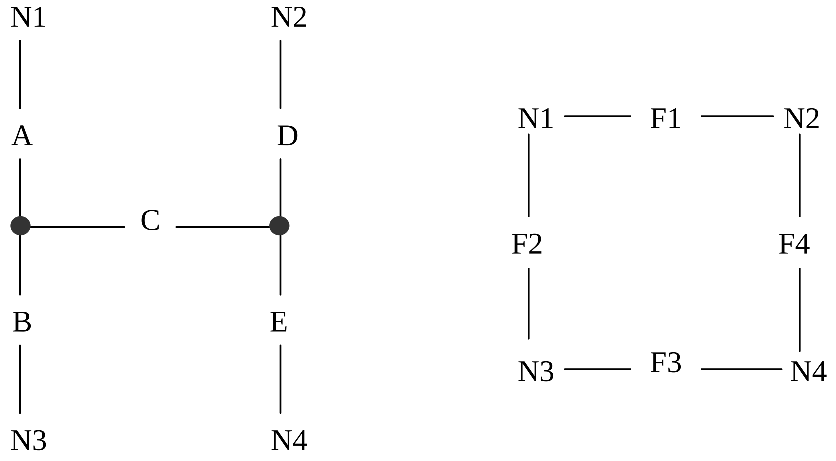
Definitions and assumptions:

- An SRLG is a set of links sharing a common physical resource i.e. a common risk.
- The set of links said to belong to the same SRLG, if they are established over fibers that go through the same fiber sub- segments (so through the same fiber trunk) and through the same fiber segment between two nodes.
- A lightpath is defined to cover an SRLG iff (if and only if) it crosses one of the links belonging to that SRLG.
- Two lightpaths are defined as diverse with respect to a set of SRLGs iff the sets of SRLGs they cover are disjoint.

Example:

The following example referring to Figure 5 (for the physical network topology) offers some clarification. Let assume that:

- N1, N2, N3, and N4 represent locations that are linked by the fiber sub-segments,
- A, B, C, D and E be fiber segments,
- F1 (ACD), F2 (AB), F3 (BCD) and F4 (DE) are fibers routed over the fiber segment topology.



Fiber segment topology

Fiber link topology

Figure 4. A Correlation between Fiber segment topology and Fiber link topology

In such a physical topology the obvious SRLGs are the following:

- {F1, F2} both going down when segment A breaks
- {F1, F3} both going down when segment C breaks
- {F1, F4} both going down when segment D breaks
- {F2, F3} both going down when segment B breaks
- {F3, F4} both going down when segment E breaks

These five SRLGs can be replaced by two SRLGs, S1 = {F1, F2, F3} and S2 = {F1, F3, F4}, where S1 and S2 constitute the minimum edge covering with cliques (note: A clique of a graph G is a sub-graph of G in which every two nodes are connected by an edge) of the Shared Risk Relationship (SRR) graph that can be drawn between F1, F2, F3, F4 (see Figure 5). This decomposition is unique. If there was a dependency between F2 and F4, there would be a unique SRLG, S = {F1, F2, F3, F4}.

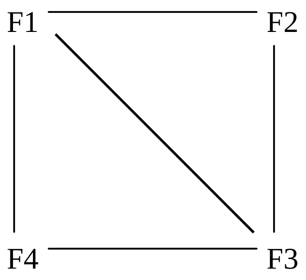


Figure 5. SRR Graph between Fiber trunks (F1, F2, F3 and F4) with respect to Fiber segment failure

Although R1 = F1-F2-F3 and R2 = F4 are diverse lightpath routes between N2 and N4 in the fiber topology (link and node disjointness), they are not diverse with respect to the SRLGs, because both R1 and R2 cover SRLG S2, which contains F1, F3 (part of R1) and F4 (part of R2). SRLGs are thus a way of formalizing the propagation of link risk dependencies from server layers to client layers.

The rules guiding the definition of minimum set of SRLGs for more complex physical network topologies will be addressed in a future version of this study.

1.2 Rationale for the SRLG Inference Model

We define the routing diversity requirement of a lightpath as the SRLG Inclusion Set (SIS) of all the lightpaths from which a given lightpath must be physically diverse. When client layers implement their own recovery mechanism, they may not want to request protected lightpaths (for instance, a client could only request unprotected lightpaths from the optical network). However, the client may request that some of these unprotected lightpaths be diverse throughout the optical network, such that corresponding links in the client layer topology do not fail together or at least, are unlikely to fail together.

The SLRG Inclusion Set (SIS) of a lightpath is defined as the set of SRLGs covered by this lightpath. As mentioned in before, routing diversity could be related to the following physical optical network resources:

- Node (not considered in this document)
- Fiber link
- Fiber sub-segment
- Fiber segment
- Fiber trunk

The SRLG Resource identifiers (SRLG Resource ID) corresponding to the optical network resources can be defined by considering a hierarchical encoding as defined in Section 3:

- Optical device: Node ID
- Fiber link: Identified by a Fiber ID (and a Fiber ID – Port ID mapping table)
- Fiber sub-segment: Identified by a Fiber Sub-segment ID
- Fiber segment: List of fiber sub-segments included within the same segment; coded as Fiber Segment ID
- Fiber trunk: Sequence of fiber sub-segments connecting two nodes

1.2.1 Lightpath Creation

When a client node sends a lightpath create request to the boundary node, it can only reference lightpath(s) from which the new lightpath j should be diverse. This because we assume that the client only knows about the lightpaths it has already established. The purpose is to avoid the set of SRLGs contained in the SISs of lightpath 1, lightpath 2, ..., lightpath N when routing lightpath j.

The node will process this request by considering the Shared Risk Link Groups (SRLGs) of the lightpath 1, lightpath 2, ..., lightpath N and find a physical route for the lightpath j whose SIS does not contain any of the SRLGs covered by the lightpath 1, lightpath 2, ..., lightpath N. Consequently, the SIS of the lightpath j could be represented as the union of the SIS of the lightpaths from which the lightpath j has to be diverse.

Each of the physical resources included within the optical network could be allocated to a lightpath. Consequently, there is a corresponding list of lightpaths sharing a common resource identified by a resource type and a resource ID that could be represented as a resource allocation array:

[<<RT 1; RID 1> ; <LPSet[1,1]>>
<<RT 1; RID 2> ; <LPSet[1,2]>>
...
<<RT 1; RID N[1]> ; <LPSet[1,n]>>
...
<<RT 2; RID 1> ; <LPSet[2,1]>>
<<RT 2; RID 2> ; <LPSet[2,2]>>
...
<<RT 2; RID N[2]> ; <LPSet[2,n]>>
...

...

<<RT M; RID 1>	; <LPSet[m,1]>>
<<RT M; RID 2>	; <LPSet[m,2]>>
...	
<<RT M; RID N[M]>	; <LPSet[m,n]>>]

where

- RT: Resource Type (such as Fiber, Fiber sub-segment, Fiber segment, Fiber trunk)
- RID: Resource Identifier for a given RT.
- LPSet[i,j] := Set of Lightpaths covering a RT i having a RID j

Since each of these lightpath sets shares a common resource each of these resources constitutes a shared risk. Hence, in the optical channel layer, the corresponding lightpath sets constitutes an SRLG for a given (RT, RID) pair.

If we consider the fiber set allocated to the optical network topology, then there is a corresponding list of fibers sharing a common resource and identified by a (RT, RID), as illustrated below:

[<<RT 1; RID 1>	; <FLSet[1,1]>>
<<RT 1; RID 2>	; <FLSet[1,2]>>
...	
<<RT 1; RID N[1]>	; <FLSet[1,n]>>
...	
<<RT 2; RID 1>	; <FLSet[2,1]>>
<<RT 2; RID 2>	; <FLSet[2,2]>>
...	
<<RT 2; RID N[2]>	; <FLSet[2,n]>>
...	
...	
<<RT M; RID 1>	; <FLSet[m,1]>>
<<RT M; RID 2>	; <FLSet[m,2]>>
...	
<<RT M; RID N[M]>	; <FLSet[m,n]>>]

Where: FLSet[i, j] := Set of Fiber Links covering a RT i having a RID j

In this case, each of these fiber sets shares a common resource meaning that each of these resources constitutes a shared risk Hence in the physical layer, the corresponding fiber sets constitutes an SRLG for a given (RT, RID) pair. Note that this discussion including the one related to the LPSet does not include the logical structure to which a resource belongs.

Consequently, the routing diversity of a lightpath X (so, extendedly the SRLG Inclusion Set of a lightpath X will be defined as the corresponding complement) can be represented as the list of all the resources covered by all the lightpaths from which this lightpath X has to be physically diverse from (i.e. the set of resources that must not be used the lightpath X):

[<<RT 1>; <RID 1, RID 2, ..., RID K>>

<<RT 2>; <RID 1, RID 2, ..., RID L>>

…

<<RT N>; <RID 1, RID 2, ..., RID M>>]

This means exclude lightpath X from:

- RT 1 is identified by excluding <RID1,..., RID K>
- RT 2 is identified by excluding <RID1,..., RID L>
- …
- and RT N is identified by excluding <RID1,..., RID M>.

However, this interpretation does not permit to find the relationship between logical structures or physical resources: for instance a fiber is included in a fiber sub-segment, which is included in a fiber segment. Moreover, several lightpaths can be included within the same fiber (or link). As defined in [IPO-FRAME], the notable characteristic of SRLGs is that a given link could belong to more than one SRLG, and two links belonging to a given SRLG may individually belong to two other SRLGs. The algorithm described in the section 1.4 of this Appendix, propose a method to dynamically discover these relationships.

1.2.2 Risk Type

As specified up to now, the SRLG model specification considers that each of the resource (as used in the lightpath computation) may experience one or more failure type(s). The same applies to geographical locations - a given location might be subjected to more than one failure type. Moreover, by applying the SRLG properties, a network resource failure could cover more than one geographical location. Consequently, some heuristics must be introduced to keep the SRLG computational complexity limited.

In order to limit the computational complexity, we define the following heuristics when considering the SRLG computation with respect to the type of risk:

1. The set of risk types associated to network resources corresponds exactly to the set of resource type failure. So, for instance, the risk type associated to a fiber segment is a fiber segment failure. The same principle applies for other network resources such as fiber link, fiber sub-segment and fiber trunk. Consequently, we don’t consider a finest granularity for the network resource failure than the one referred by their type.

2. A risk type associated to a geographical structure covers exactly the region where it is defined. Moreover, a geographical failure is limited to a given location and does not impact the neighboring locations or generate another geographical failure type. For instance, we consider that an earthquake covers exactly one region or one area and that such a failure does not generate a hurricane impacting the neighboring locations. So, there is no correlation between geographical failures.

3. Each of the network resources covers exactly one geographical logical structure (defined by a region ID or a zone ID). Consequently, when a geographical failure occurs, it generates a failure impacting the entire network resources included within the corresponding location. Hence, there is an ON/OFF relationship between geographical and network resource failures.

Consequently, when considering network resources, the risk type associated to an SRLG is defined as the potential failure of one (or more than one) instance of the resource belonging to a given resource type or the potential failure of one (or more than one) instance of the resource depending on one (or more than one) of the instance of this given resource.

In the previous section, we defined the concept of SRLG with respect to a given resource type (and by extension to the risk type to which this resource type refers) and a given resource identifier by means of the lightpath and fiber set concept. This definition can be extended to include the fiber sub-segment and fiber segment set concept. Since each instance of these sets corresponds to an SRLG class, we assign an identifier to each of the SRLG classes members and define this value as a SRLG identifier.

Moreover, by applying the defined heuristics above, the SRLG identifiers can be grouped together by taking into account their geographical location. The latter is encoded by identifying the region identifier (region ID) and the zone identifier (zone ID) including the resource identifiers to which the SRLG refers.

1.3 Calculation of Shared Risk Link Groups

In the calculation method, shared_risk(RID i, RID j, RT)is TRUE only if RID i and RID j belong to the same SRLG with respect to the type of risk (RT). The risk types considered here are related the fiber trunk, the fiber segment, the fiber sub-segment and the fiber link risk failure.

A recursive calculation of shared_risk proceeds as follows:

```
shared_risk(RID i, RID j, RT) =
        at_risk(RID i, RT)
        and at_risk(RID j, RT)
        and (RID i = RID j
                or (exists RID k, RID l
                such that
                        depends_on(RID i, RID k)
                        and depends_on(RID j, RID l)
                        and shared_risk(RID k, RID l, RT)))
```

In this calculation:

- at_risk(RID i, RT) is TRUE only if RID is susceptible to a risk of type RT, either directly, or indirectly, through the failure of one of the elements it depends on.

- depends_on(RID i, RID j) is TRUE only if RID i fails as soon as RID j fails.

If we refer to the example detailed in section 1.1, then shared_risk(F1, F2, [fiber segment failure]) = TRUE because depends_on(F1, A) = TRUE , depends_on(F2, A) = TRUE and at_risk(A, [fiber segment failure]) = TRUE (the latter simply because A *is* a fiber segment).

1.4 Practical Method for SRLG Calculation

The recursive formula presented in the previous section does not directly lead to an efficient algorithm. It's top-down nature illustrates nicely the recursive nature of the SRLG concept, but the calculation of the SRLGs in a top-down fashion would be totally inefficient, entailing the calculation of the same SRLGs in lower network layers over and over again.

A far more efficient algorithm can be obtained by a bottom-up calculation. Figure 6 illustrates this by using the example we introduced in the section 1.1 and in by introducing the concept of Shared Risk Relationship Graph (SRR) which defines the membership of a resource belonging to the same SRLG.

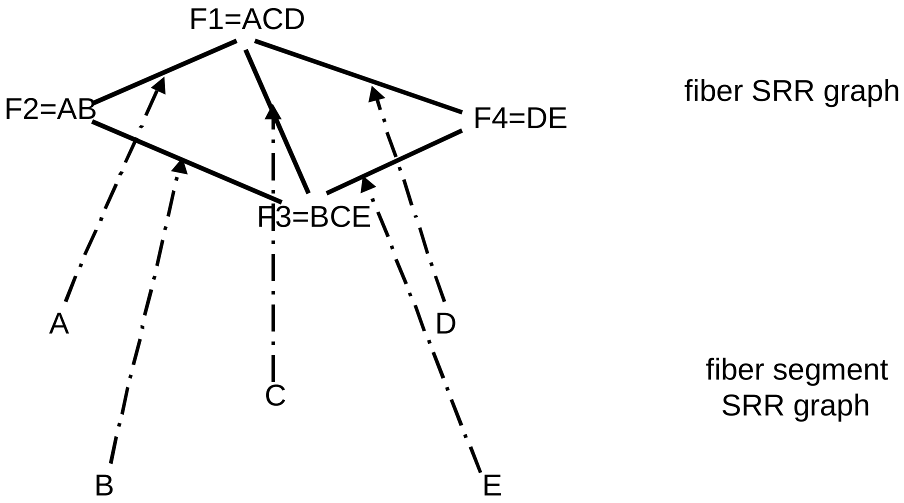


Figure 6. Bottom-up calculation of Shared Risk Relationships

For the calculation of a set of SRLGs, we need to calculate a Shared Risk Relationship (SRR) graph. The bottom-up calculation of the fiber SRR graph proceeds as follows:

– Step 1. For each fiber segment, there is an SRR between every two fibers contained in that segment (vertical arrows in Figure 6.)

- Step 2. For every SRR between two fiber segments, there is an SRR between every two fibers contained in either of the two fiber segments.

In the previous example, there are no SRRs between fiber segments, and the calculation stops after Step 1.

1.5 Application of the Model

The model is intended to be used to automate the discovery of the SRLGs at a given layer for a given risk type (RT).

The dependencies may be confined to one layer, e.g. the dependency of an optical link on a node (for instance, a DWDM end-system) to which it is connected, when the RT = [Node failure]. Dependencies may also extend over layer boundaries, e.g. the dependency of an TDM circuit in an SDH network established on an optical channel (or wavelength) through the optical network that is the server of the SDH network, when RT = [fiber failure].

Let two optical network resources RID i and RID j within the same layer share a common risk of type RT. Let this risk type be tied to a lower layer, which we will call the risk layer. To enable the layer to infer shared_risk(RID i, RID j, RT), its serving layer should advertise the following information:

shared_risk(component_1, component_2, RT)

where:

- component_1 are services of the serving layer on which RID i rely and
- component_2 are services of the serving layer on which RID j rely.

If the serving layer is not the risk layer, the latter has to infer this knowledge itself from what its serving layer is advertising.

If shared risk relationships are not advertised, client layers should at least be able to query from their serving layer the shared risk relationships between the services they receive.

Some dependencies do not lend themselves easily to automatic discovery. For instance, it is hardly imaginable that the process of finding out through which fiber segments a fiber goes can be automated. This means that part of the image of depends_on (RID i, RID j) will have to be provided ‘manually’ by the operator or be at least statically configured into a centralized repository.

More formally, an efficient calculation of shared risk link relationships relies on two things:

- In the lowest network layer with elements susceptible to the risk type RT that is considered, every network element RID j susceptible to the risk RT constitutes an SRR on its own, that is, (RID j, RID j) satisfies the recursive formula;

- Every SRR that has been discovered in one network layer leads to SRRs in the next higher network layer. In particular, two next higher layer network elements (RID i, RID j) depending on lower layer network elements that have an SRR satisfy the recursive formula. In order to allow an efficient calculation of the shared risk relationships in the next higher layer (e.g. the fiber layer), the shared risk relationships that were discovered in lower layers (e.g. the fiber segment layer) are stored in SRR graphs. This way, the recalculation of lower layer shared risk relationships can be avoided.

1.6 Generalized SRLG Inference Model

By referring to the example provided in the section 1.1, we can deduce the following statements:

- First, given a physical network, we must assign in the optical network the fibers to fiber sub-segments (this is usually trivial since a fiber sub-segment will correspond to a fiber bundle), and we must (less trivially) assign fiber sub-segments to fiber segments.

- Then, given a physical network, every fiber sub-segment that is connected to a location Ni must belong to a common fiber segment.

However one can argue that a location should be allowed to have multiple fiber segments connected to it. Consider for instance the example of a central office in a SDH/SONET network, which may be connected to a metro ring and a local access ring or a linear cascade of nodes. We can represent such a facility by a location vertex that is connected to four fiber segments in the two-ring case (two segments associated with each ring). A logistical issue is how the network will know that a particular section of a fiber bundle belongs to a particular fiber segment.

1.6.1 Connectivity Graph

So in the general case, any network at the fiber segment level can be represented as a graph G([N,X], S), where N is the set of vertices that correspond to locations set N {N1, N2, ... , Nn}, X is the set of vertices that are not locations but are meeting points for fiber segments (we call these vertices {X1, X2, ... , Xm}), and S is the set of fiber segments {S1, S2, ... , Sp}.

Similarly, the network can be represented by a fiber connectivity graph C(N,F), where the set N is equal to the set N in the fiber segment graph above, and the set F is the set of edges indicating fiber connectivity between the elements of the set N. Specifically, an edge Fi exists between two vertices Ni and Nj if and only if there exists at least one direct fiber link connection between the two locations corresponding to Ni and Nj.

Furthermore, we can say that for every edge {Ni, Nj} in C(N,F), there is a walk that can be represented as a path {Ni, Xa1, Xa2, ... , Xak, Nj} or equivalently as a trail {Sa1, Sa2, ... , Sa(k+1)} in G([N,X],S), where {Sa1, Sa2, ... , Sa(k+1)} is the trail of fiber segments (the fiber trunk) that connects Ni to Nj, and that every such walk corresponds to a fiber trunk that connects the two locations.

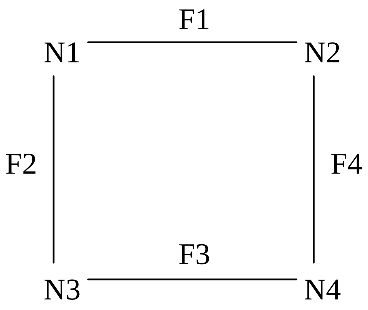


Figure 7. - Connectivity graph C(N, F)

However, it is important to note that not every path in G([N,X],S) of the form {Ni, Xa1, Xa2, ... , Xak, Nj} maps to an edge in C(N, F). There must be a corresponding edge in C(N,F) to obtain such a mapping. When referring to the above example, {N1, X1, X2, N4} is a path from N1 to N4 whose only members that are elements of N are its endpoints, but there is no direct connection between N1 and N4, as can be seen from the connectivity graph C(N,F).

1.6.2 Shared Risk Relationship (SRR) Graph

In order to construct the SRR graph, we need to find a way to combine the information in C(N,F) and G([N,X],S) to form a new graph, H(F,E) that defines the Shared Risk Relationship (SRR). In this new graph, the members of the connectivity graph C(N,F) edge set become the vertices of the SRR graph, while the edge set in H(F,E), E, is formed from subsets of the fiber segments set S.

We can perform this by using the following algorithm:

1. From the nodes of C(N,F) using the elements of F from the connectivity graph C.

2. Examine each pair of nodes Fi and Fj in F. Each element of F is associated with a set of element of S, the fiber segment set. For instance, in the above example, if the intersection of Fi and Fj is not empty, create an edge connection Fi and Fj and associate it with the set Fi (union) Fj. Using the example above, the elements, the elements of F are the following:
    - F1 = {S1, S3, S4}
    - F2 = {S1, S2}
    - F3 = {S2, S3, S5}
    - F4 = {S4, S5}

    Taking all possible intersections of these sets enables us to construct the SRR graph H(F,E) as shown here below:

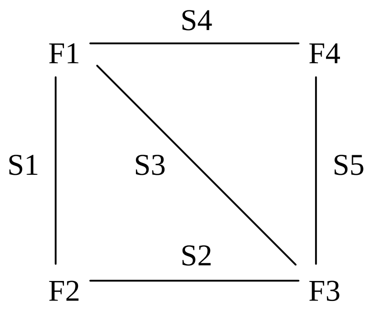


Figure 8. – Shared Risk Relationship Graph H(F,E)

In addition, if there are any fiber segments that are not contained in the union over the set of all pairwise intersections of elements of F, these should be added to the SRR graph H(F,E). The formal criteria for identifying these fiber segments, is as follows: a segment Si is a non-overlapped segment if it is not a member of:

(union) Fi (intersect) Fj
i,j

For each segment Si that meets the above criteria, add an edge to the SRR graph H(F,E) using the following procedure. Find the node that corresponds to the fiber path that contains Si. Attach a loop to the node and label it Si.

3. Form the set of first-tier SRLGs by first taking the set of all edges of the graph H(F,E). Next examine the vertices of H(F,E). If there are any elements of any of the Fi's that are not contained in the set of first-tier SRLGs, add these elements to the set as well.

4. A second-tier set of SRLGs can be developed by forming a covering of H(F,E). A simple way to do this is to require that the covering be composed using cliques. (A clique is a sub-graph in which every vertex is connected to every other vertex and there are no loops or multiple connections between any vertex pairs.) The SRLG associated with a clique is the union of the set of fiber segments that are associated with the edges of the clique.

   Each element of S defines an arc in G([N,X],S), rather than an edge, since in the general case we cannot assume that the existence of a connection between two nodes in a given direction implies the existence of a connection between those two nodes in the other direction.

   In the example that we have considered, each arc in the SRR graph has only one fiber segment associated with it, but this does not have to be the case in general. Consider the network shown in Figure 9. In this case we also have five distinct fiber segments, but the topology gives us the graphs G([N,X],S) and C(N,F) as shown in Figure 10(a) and Figure 10(b), respectively. When we form the SRR graph, we get H(R,E) as shown in Figure 11. Note that in this case the intersection of fiber paths F2 = {S1, S3, S4} and F3 ={S2, S3, S4} yields the set {S3, S4}, which is the SRLG associated with those two fiber paths because the loss of either fiber segment S3 or segment S4 will result in the disruption of traffic on both fiber paths.

To obtain the full set of first-tier SRLGs for the network in Figure 9, we first examine the edges of the SRR graph in Figure 11 are S1, S2, {S3, S4}, and S4. Examining the vertices of the SRR graph reveals that we must add S5 to the list of first-tier SRLGs as well (S5 is an SRLG unto itself). There are two cliques that are sub-graphs of the SRR graph; these give us the second-tier SRLGs {S1, S2, S3, S4} and {S3, S4, S5}.

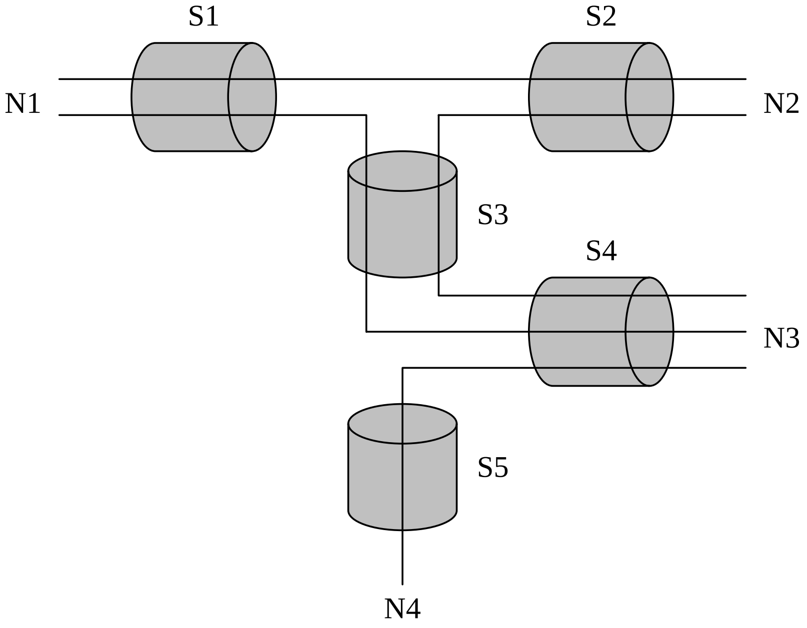


Figure 9. Second Example of Network Topology

Note that fiber paths {S1, S3, S4} and {S2, S3, S4} can be broken by the loss of fiber segment S3 or fiber segment S4.

The following figures represent the graphs G([N,X],S) and C(N,F) for the network topology defined by Figure 9.

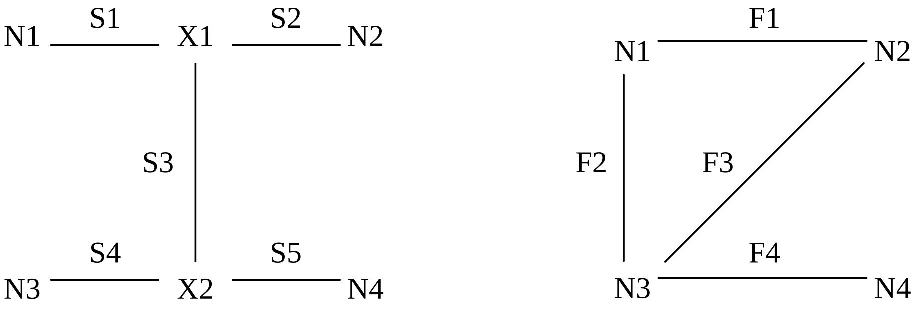


Figure 10. Graphs G([N,X],S) and C(N,F)

In Figure 10(b), the Fi’s (i.e. the fiber paths) are defined as follows:

- F1 = {S1, S2}
- F2 = {S1, S3, S4}
- F3 = {S2, S3, S4}

- F4 = {S4, S5}

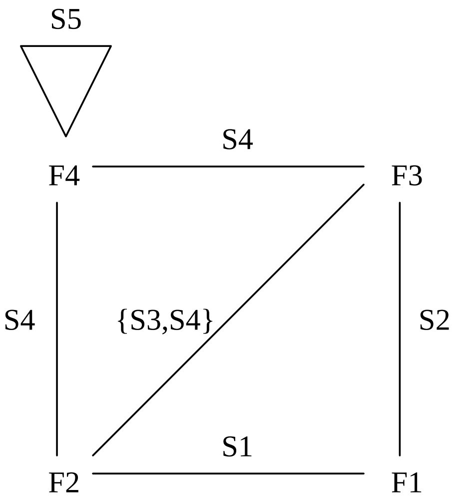


Figure 11. The SRR Graph H(F,E) for the network in Figure 9

Then we consider the case where fiber segments are not terminated at intermediate nodes. An example of this would be a ring network where certain fibers are not attached to local add-drop multiplexers at a given station because none of the traffic that they are carrying needs to be groomed at that node. A ring network with fiber pass-through is shown in Figure 12 where the connections from N1 to N4 and N2 to N3 are passed through nodes N3 and N4, respectively.

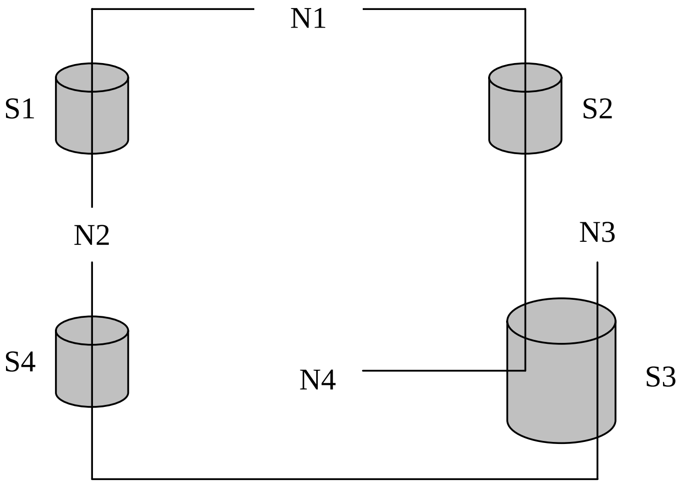


Figure 12. A ring network with fiber pass-through at some nodes.

In the network in Figure 12, there are four fiber segments, as shown, and the following three fiber paths: {S1}, {S2, S3} and {S3, S4}. We can build a set of SRLGs for this network using the techniques described above. However, we should note that if node N3 experiences a catastrophic failure, this will impact two of the three fiber paths shown. Thus it is desirable to expand the definition of a fiber path to include traversed vertices in the set N in addition to elements of S. If we do this, the fiber paths in Figure 12 become {S1}, {S2, N3, S3}, and {S3, N4, S4}. The SRR graph H(F,E) for this network is left for further study.

Finally we consider another example of this would be a network where certain fibers are not attached to local add-drop multiplexers at a given station because none of the traffic that they are carrying needs to be groomed at that node. A network with fiber pass-through at some nodes is shown in Figure 13. In this example, the connection from N1 to N4 passes through nodes N2 and N3 without undergoing O/E/O conversion. Likewise the connection from N1 to N3 passes through node N2 without being terminated there.

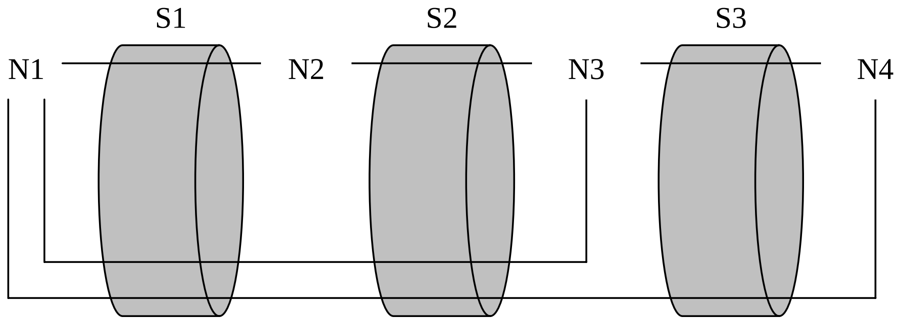


Figure 13. A network with fiber pass-through at some nodes.

In the network in Figure 12, there are three fiber segments, as shown, and the following fiber paths: {S1}, {S2}, {S3}, {S1, S2}, and {S1, S2, S3}. We can build a set of SRLGs for this network using the techniques described above. However, we should note that if either node n_2 or n_3 experiences a catastrophic failure, this will impact multiple fiber paths. Thus it is desirable to expand the definition of a fiber path to include traversed vertices in the set N in addition to elements of S. If we do this, the fiber paths in Figure 13 become {S1}, {S2}, {S3}, {S1, N2, S2}, and {S1, N2, S2, N3, S3}. The SRR graph H(F,E) for this network has the form shown in Figure 14.

In Figure 14 we have applied the rules for constructing the SRR graph that were discussed previously. The graph reflects the fact that a failure at N2 will affect fiber path F4 and F5. Note also that node N3 is represented by a loop attached to vertex F5, as that node affects only the fiber path from N1 to N4.

In Figure 14, the Fi’s (i.e. the fiber paths) are defined as follows:

- F1 = {S1}
- F2 = {S2}
- F3 = {S3}
- F4 = {S1,N1,S2}
- F5 = {S1,N2,S2,N3,S3}

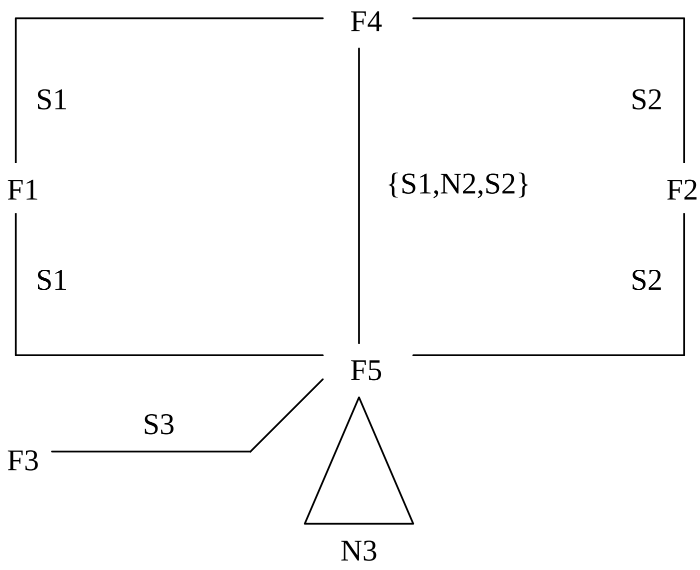


Figure 14. The SRR Graph H(F,E) for the network in Figure 13