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(54) PRIMARY/RESTORATION PATH CALCULATION IN MESH NETWORKS BASED ON MULTIPLE-COST CRITERIA

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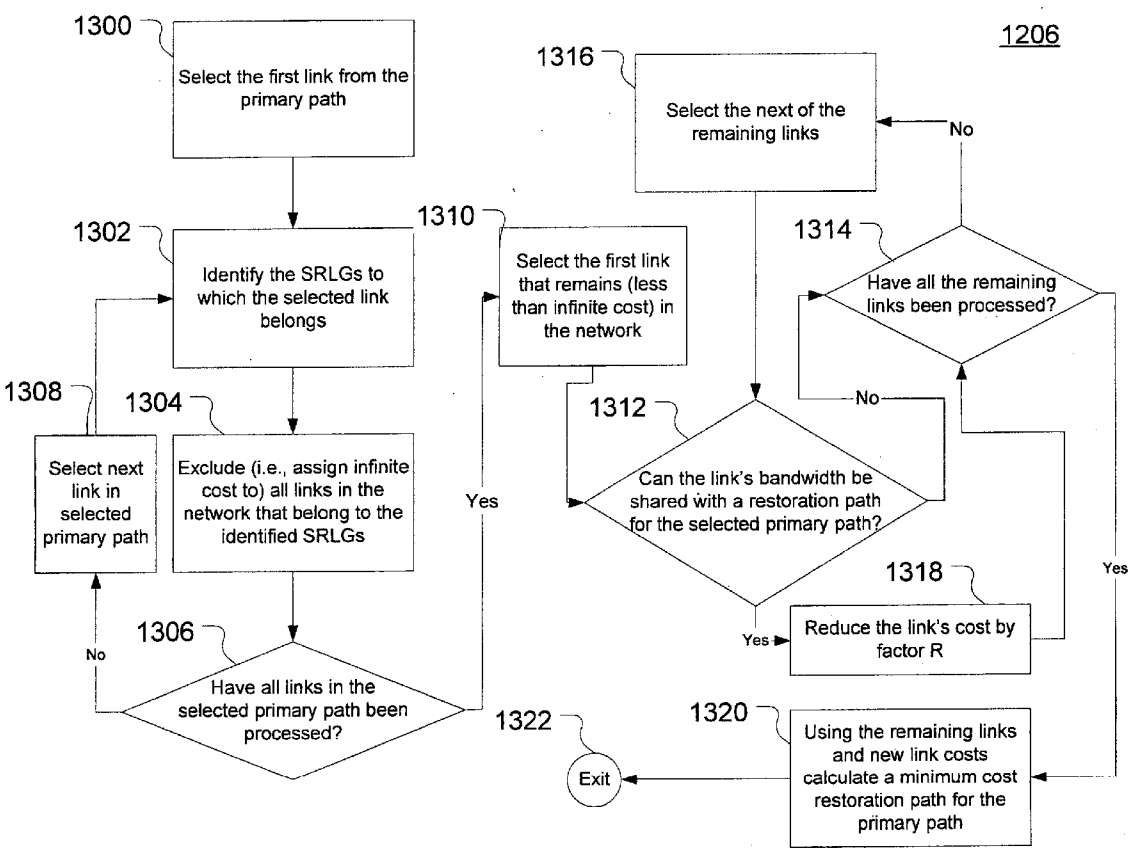
(57) **ABSTRACT**

A method for determining primary and restoration paths for a new service in a mesh network involves (1) for each of a plurality of candidate primary/restoration path pairs for the new service, generating a path cost for each candidate pair, where the path cost for each restoration path is a function of the sum of the cost of links within the restoration path, and (2) selecting the primary and restoration paths for the new service from the plurality of candidate path pairs based on the path cost. If no sharing is possible, for low utilization links, the cost of links is a function of the administrative weight of the link, whereas for high utilization links, the link cost is a function of the inverse of the available capacity on the link. If sharing is possible, the cost is a function of the inverse of a sharing degree for the link.



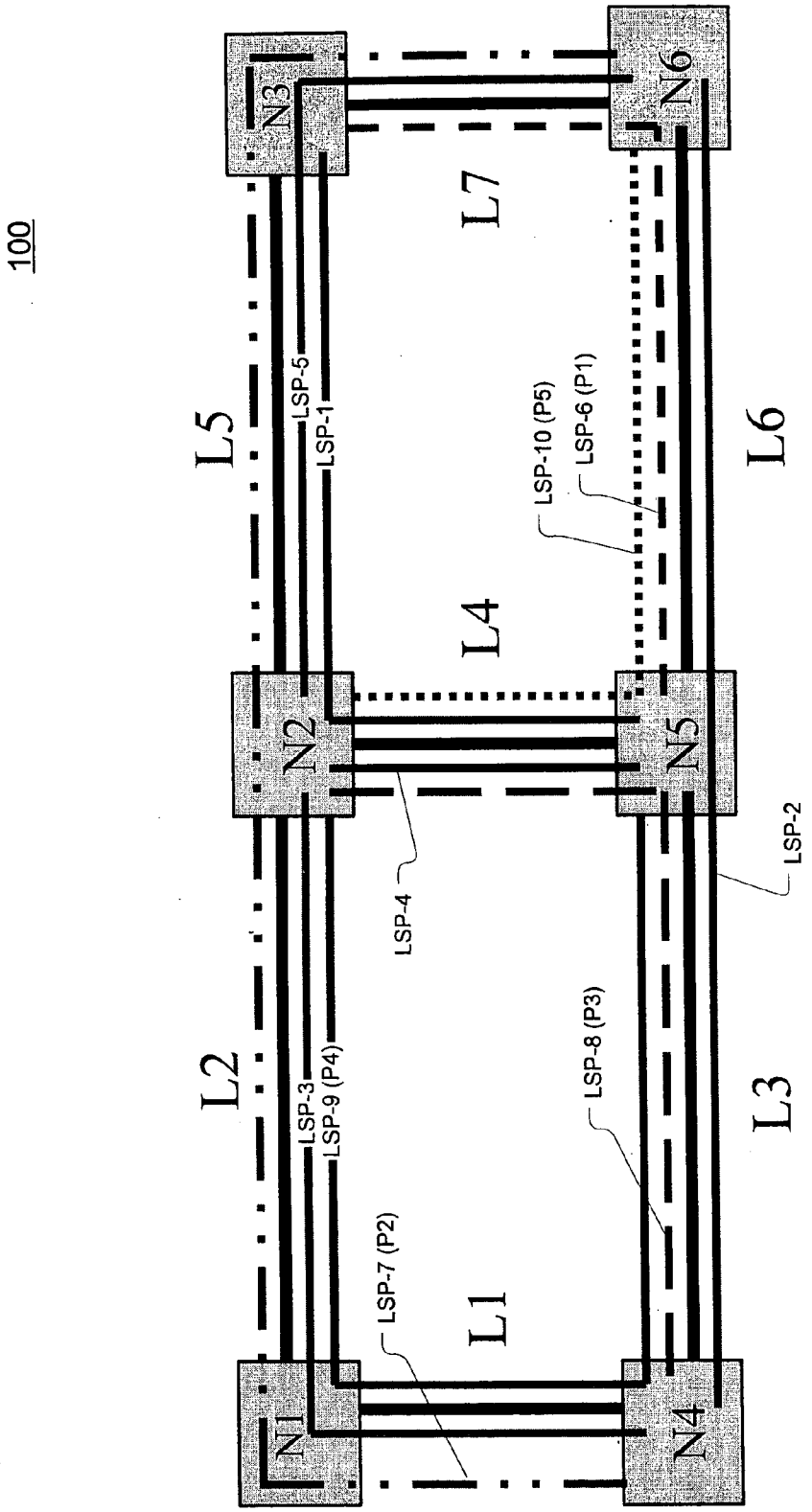

100
N1
N2
N3
N4
N5
N6
L1
L2
L3
L4
L5
L6
L7
LSP-1
LSP-2
LSP-3
LSP-4
LSP-5
LSP-6 (P1)
LSP-7 (P2)
LSP-8 (P3)
LSP-9 (P4)
LSP-10 (P5)

FIG. 1

TABLE 1

Link	L1	L2	L3	L4	L5	L6	L7	N1	N2	N3	N4	N5	N6	Max
L1			1	1		1						1		1
L2			1	1		1						1		1
L3	1	1		1				1						1
L4	1	1			1		1	1		1				1
L5			1			1						1		1
L6				1	2		1		1	1				2
L7			1	1	1	1			1			1		1

FIG. 2

TABLE 2

Link	L1	L2	L3	L4	L5	L6	L7	N1	N2	N3	N4	N5	N6	Max
L1			2	2		1						2		2
L2			2	2		1						2		2
L3	1	1		1				1						1
L4	1	1			1		1	1		1				1
L5			1			1						1		1
L6				1	2		1		1	1				2
L7			1	1	1	1			1			1		1

FIG. 3

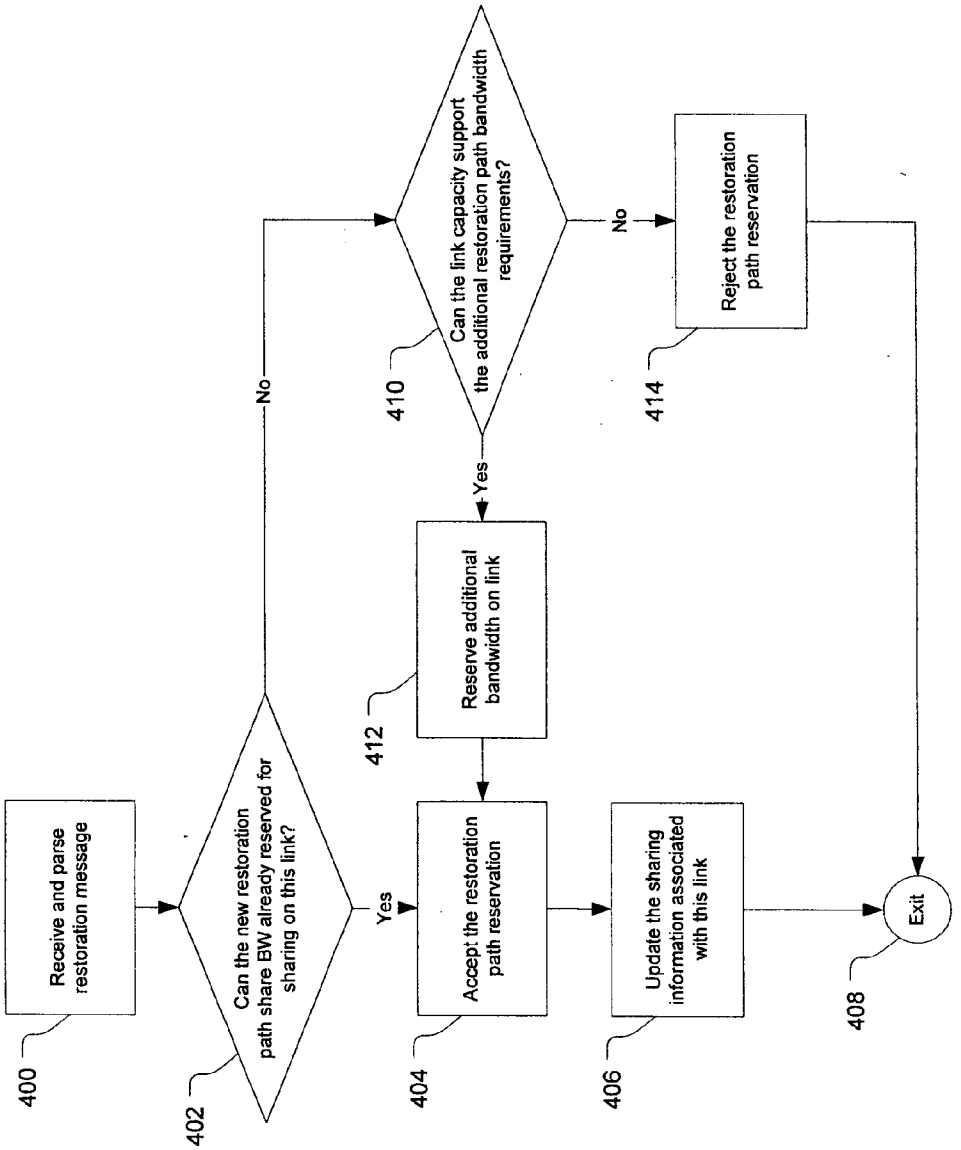

Receive and parse restoration message
400
Can the new restoration path share BW already reserved for sharing on this link?
402
Yes
No
Accept the restoration path reservation
404
Update the sharing information associated with this link
406
Exit
408
Reserve additional bandwidth on link
412
Can the link capacity support the additional restoration path bandwidth requirements?
410
Yes
No
Reject the restoration path reservation
414

FIG. 4

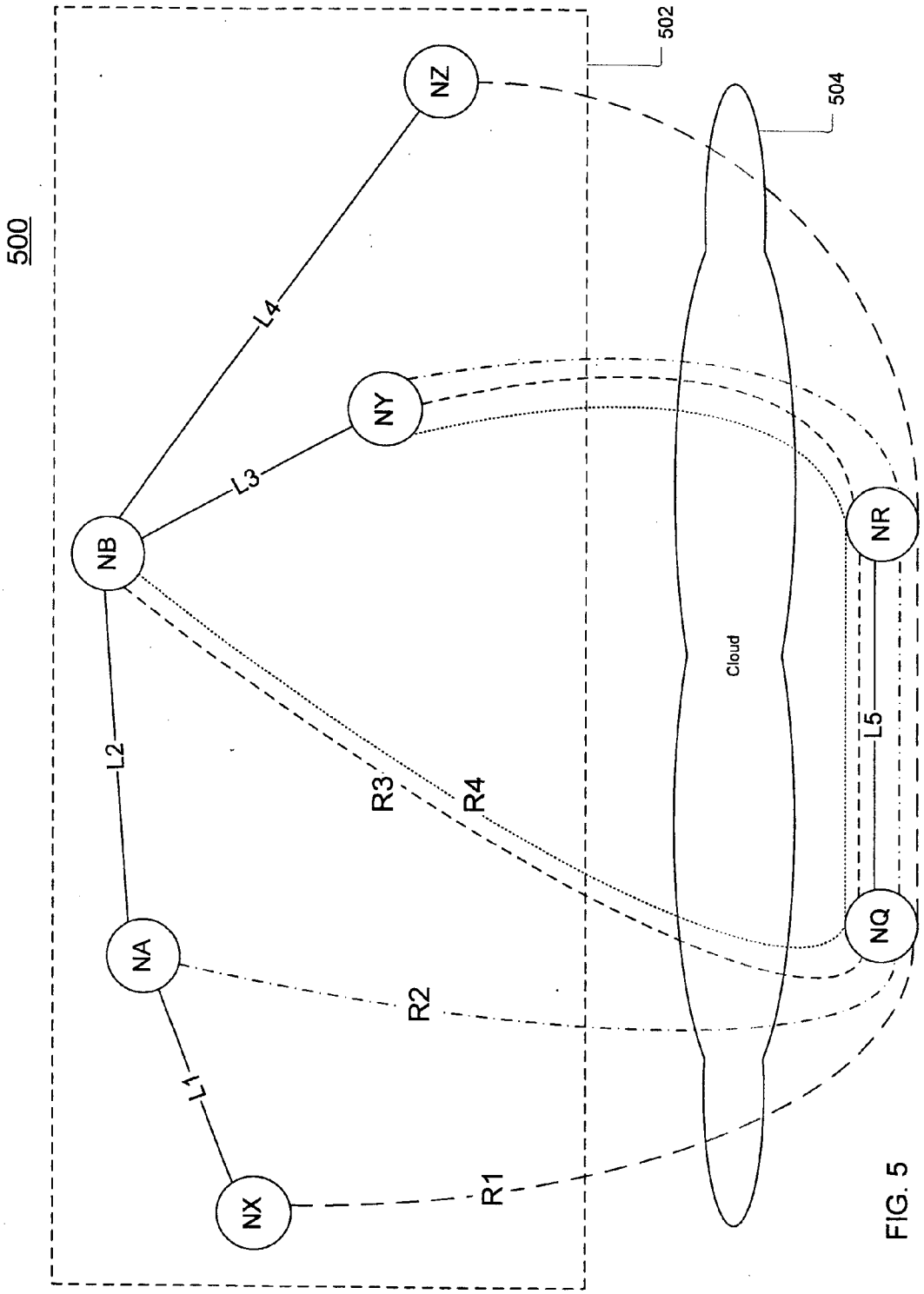


FIG. 5

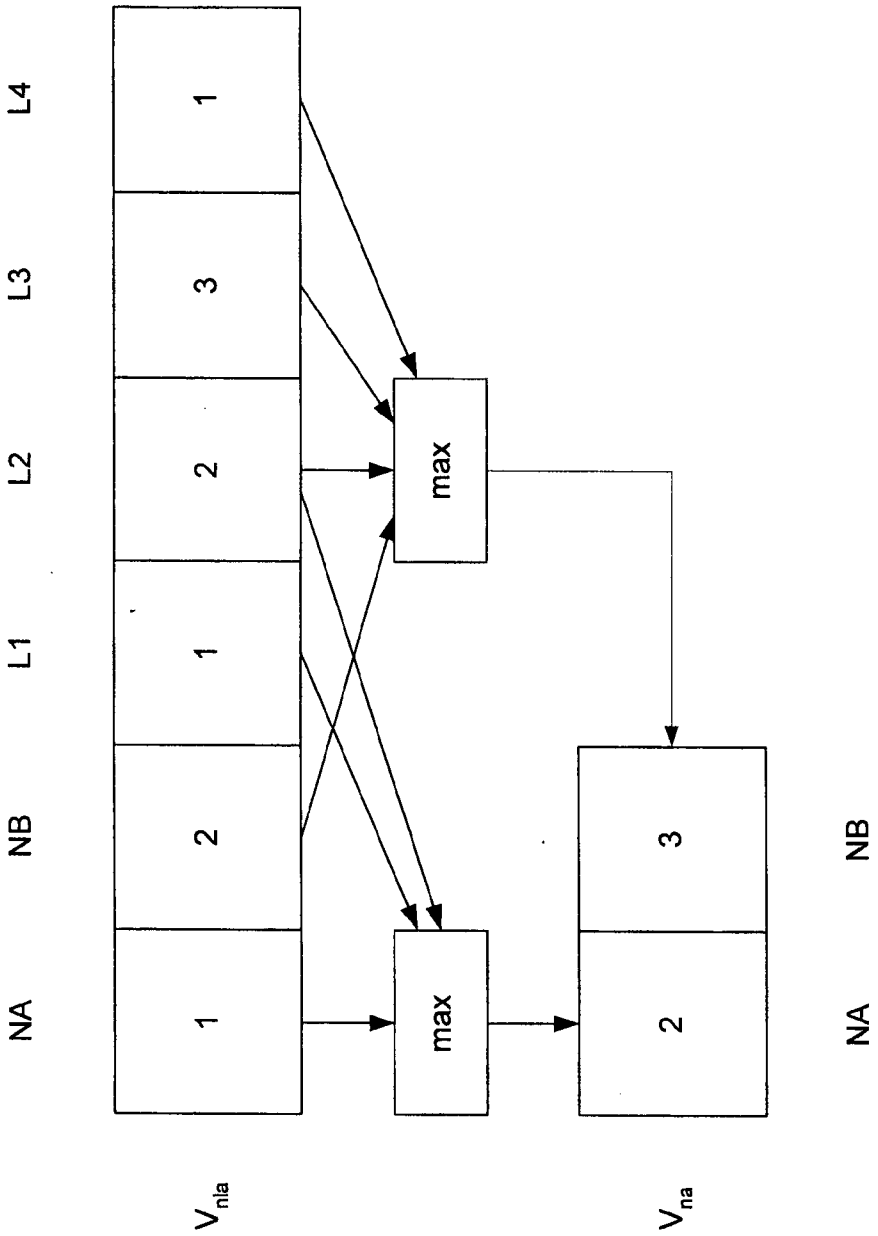


FIG. 6

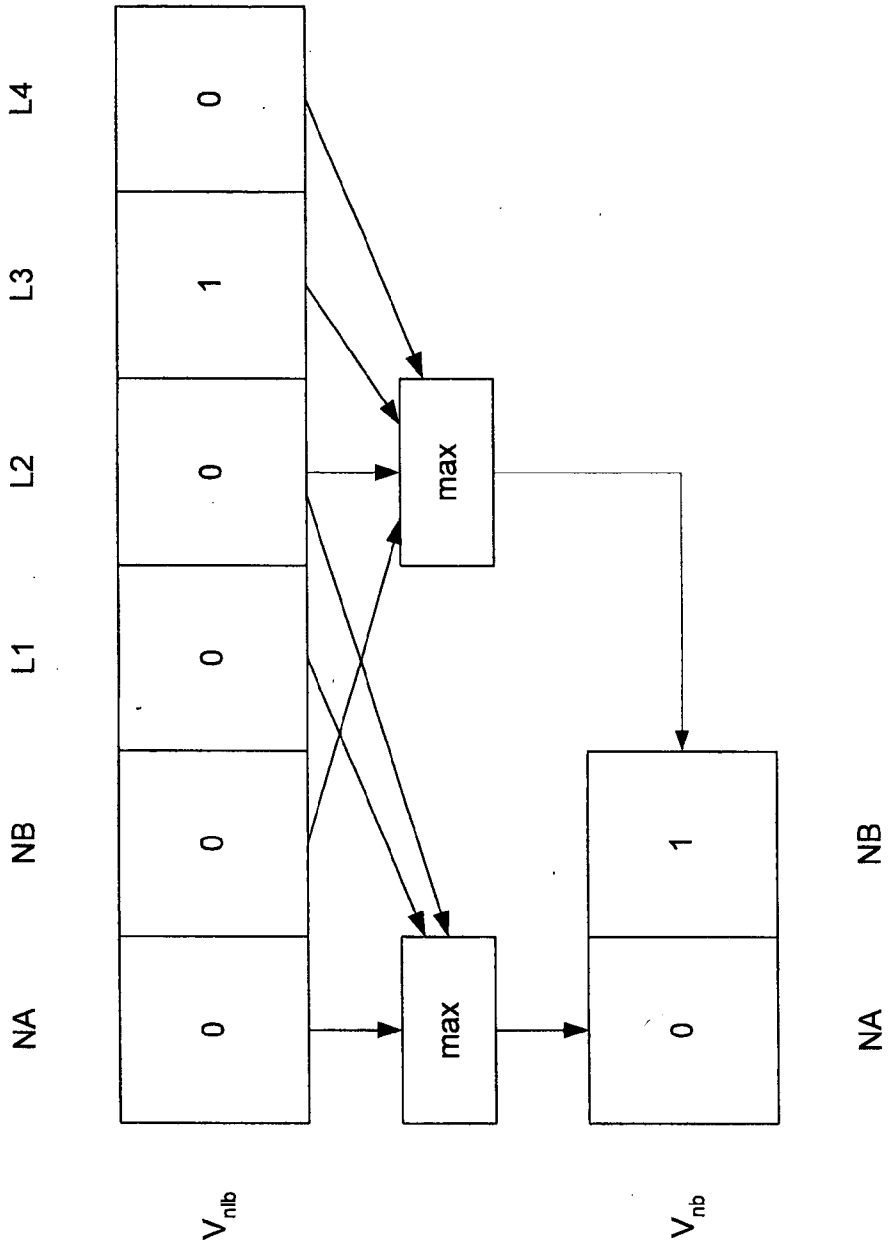


FIG. 7

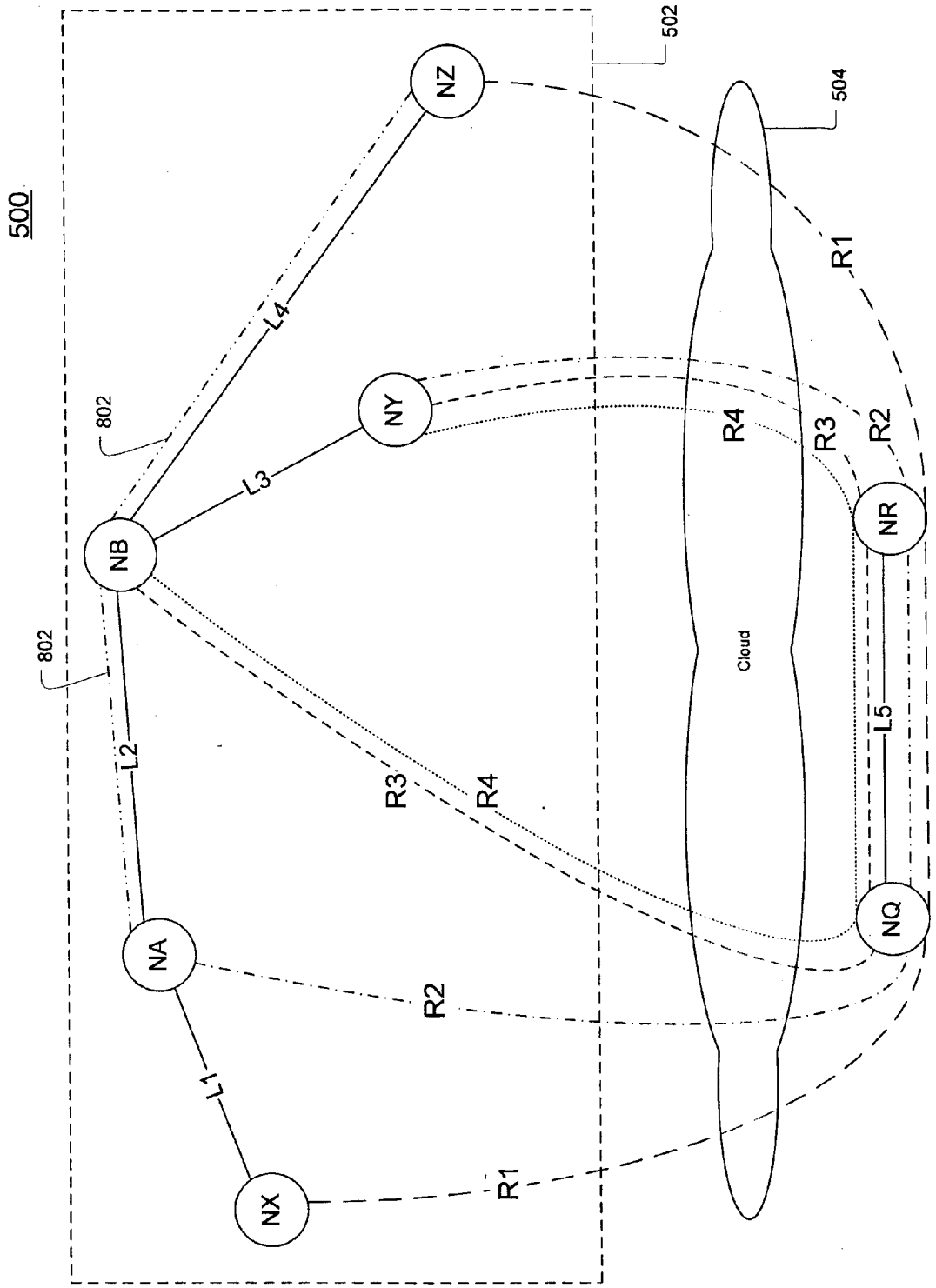

500
502
504
NZ
NY
NB
NA
NX
NR
NQ
L1
L2
L3
L4
L5
R1
R2
R3
R4
802
802
Cloud

FIG. 8

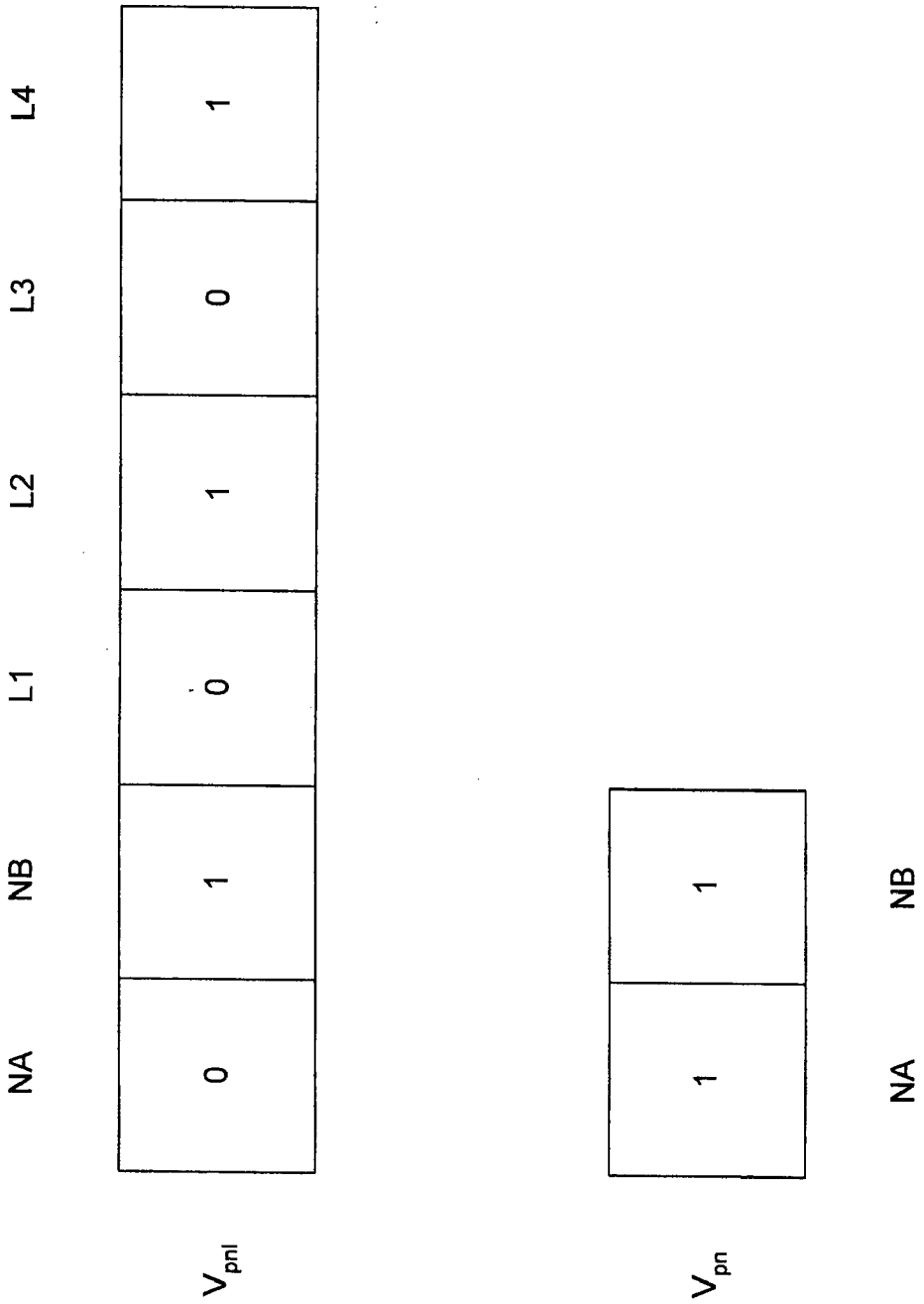


FIG. 9

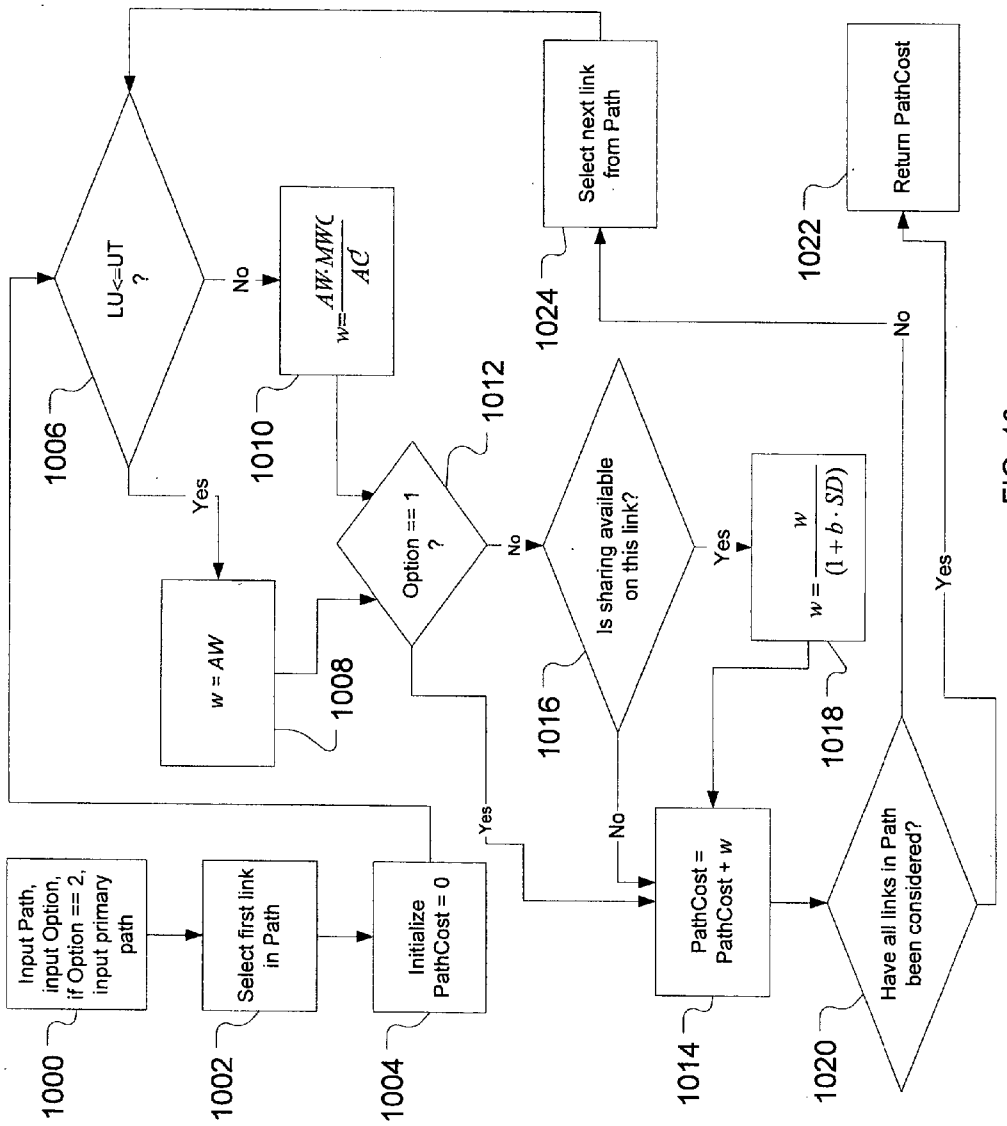

Input Path, input Option, if Option == 2, input primary path
1000
Select first link in Path
1002
Initialize PathCost = 0
1004
LU<=UT ?
1006
Yes
No
w = AW
1008
$w = \frac{AW \cdot MWC}{AC}$
1010
Option == 1 ?
1012
Yes
No
Is sharing available on this link?
1016
Yes
No
$w = \frac{w}{(1 + b \cdot SD)}$
1018
PathCost = PathCost + w
1014
Have all links in Path been considered?
1020
Yes
No
Select next link from Path
1024
Return PathCost
1022

FIG. 10

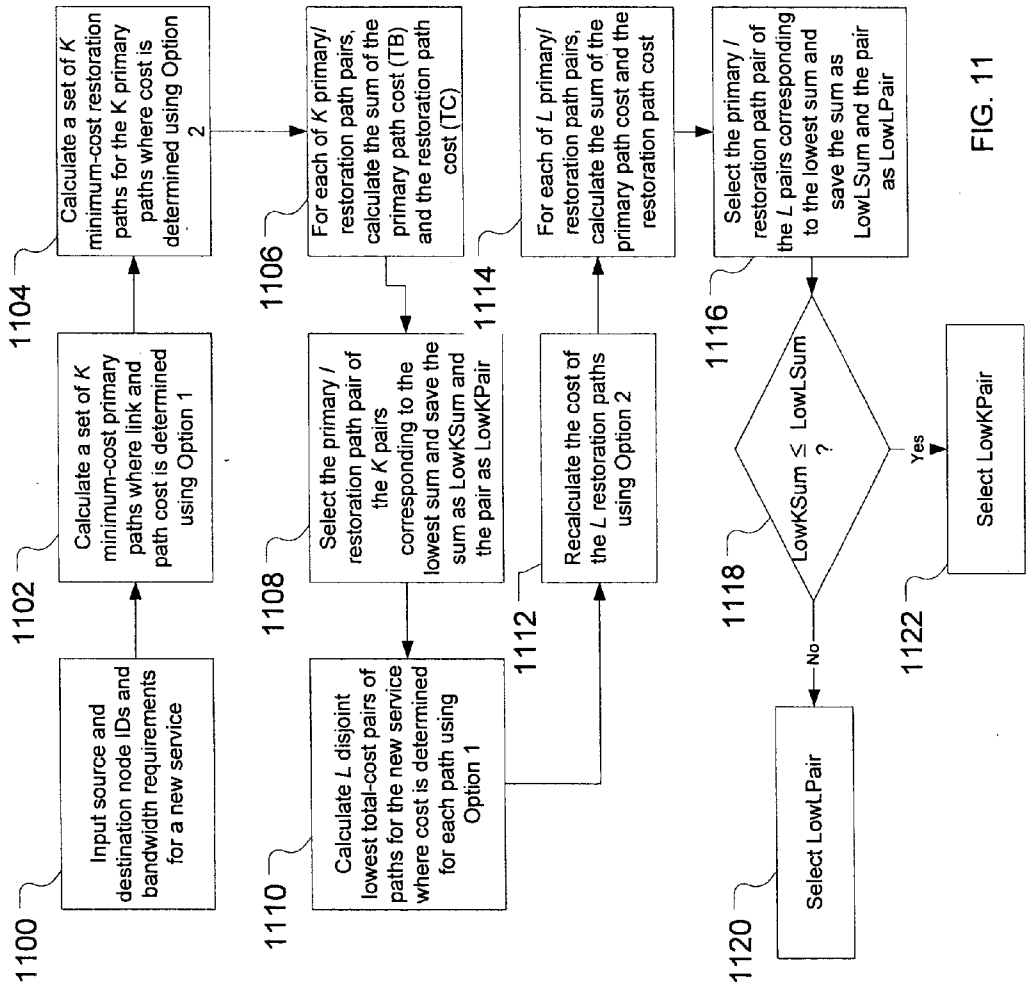

1100
Input source and destination node IDs and bandwidth requirements for a new service
1102
Calculate a set of K minimum-cost primary paths where link and path cost is determined using Option 1
1104
Calculate a set of K minimum-cost restoration paths for the K primary paths where cost is determined using Option 2
1106
For each of K primary/ restoration path pairs, calculate the sum of the primary path cost (TB) and the restoration path cost (TC)
1108
Select the primary / restoration path pair of the K pairs corresponding to the lowest sum and save the sum as LowKSum and the pair as LowKPair
1110
Calculate L disjoint lowest total-cost pairs of paths for the new service where cost is determined for each path using Option 1
1112
Recalculate the cost of the L restoration paths using Option 2
1114
For each of L primary/ restoration path pairs, calculate the sum of the primary path cost and the restoration path cost
1116
Select the primary / restoration path pair of the L pairs corresponding to the lowest sum and save the sum as LowLSum and the pair as LowLPair
1118
LowKSum ≤ LowLSum ?
Yes
No
1120
Select LowLPair
1122
Select LowKPair

FIG. 11

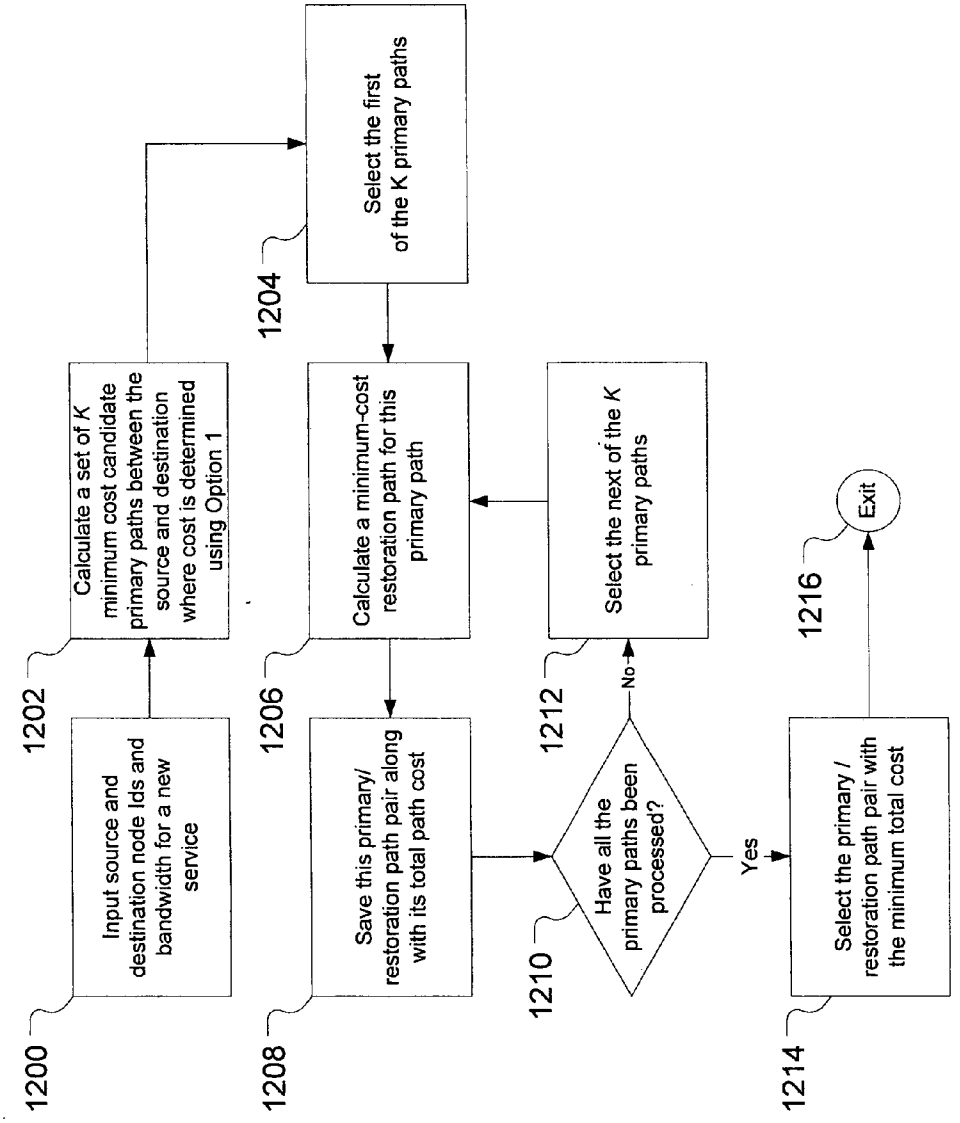

1200
Input source and destination node Ids and bandwidth for a new service
1202
Calculate a set of K minimum cost candidate primary paths between the source and destination where cost is determined using Option 1
1204
Select the first of the K primary paths
1206
Calculate a minimum-cost restoration path for this primary path
1208
Save this primary/ restoration path pair along with its total path cost
1210
Have all the primary paths been processed?
No
Yes
1212
Select the next of the K primary paths
1214
Select the primary / restoration path pair with the minimum total cost
1216
Exit

FIG. 12

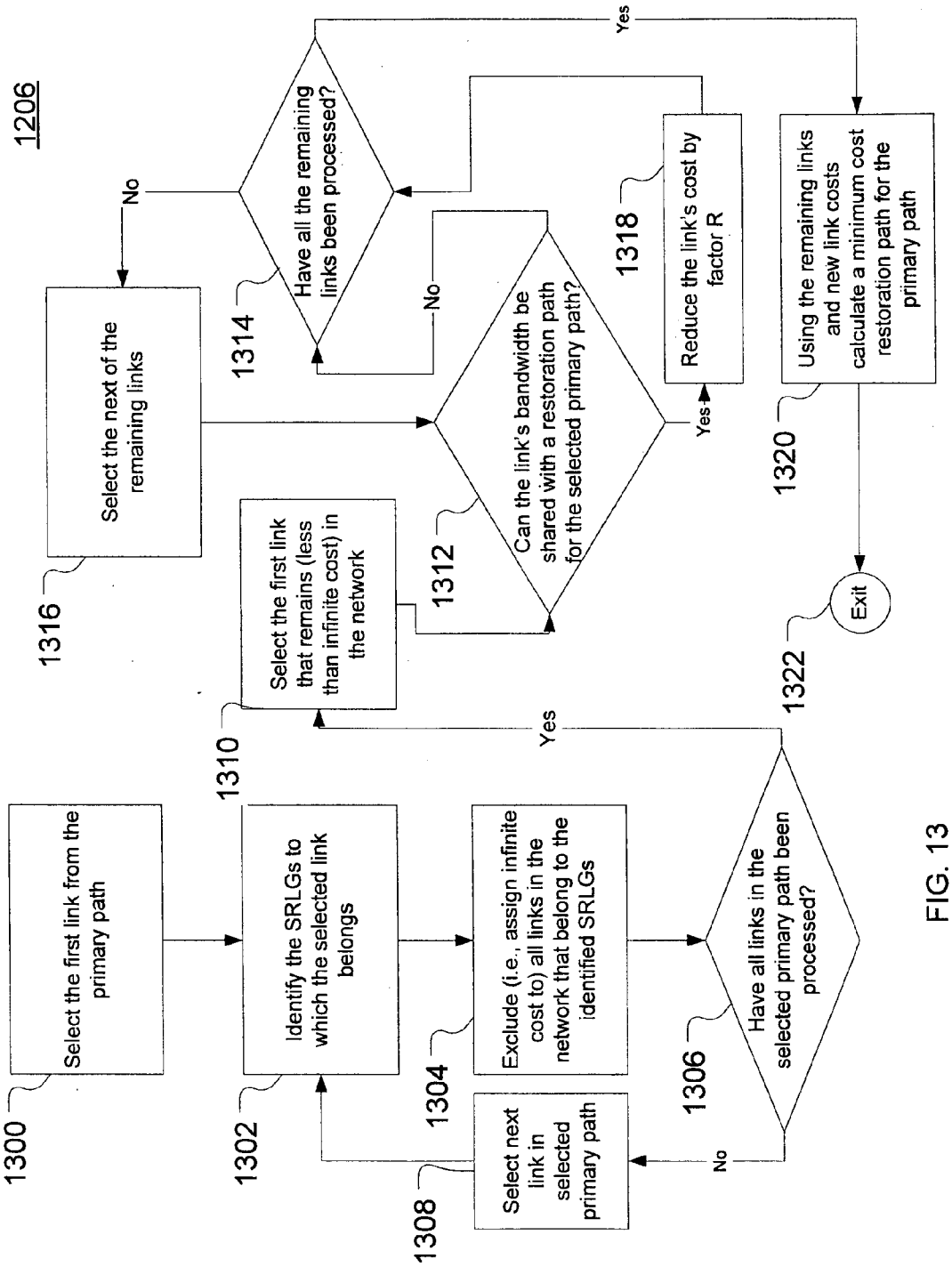

1206
Select the first link from the primary path
1300
Identify the SRLGs to which the selected link belongs
1302
Exclude (i.e., assign infinite cost to) all links in the network that belong to the identified SRLGs
1304
Select next link in selected primary path
1308
Have all links in the selected primary path been processed?
1306
No
Yes
Select the first link that remains (less than infinite cost) in the network
1310
Can the link's bandwidth be shared with a restoration path for the selected primary path?
1312
Yes
No
Reduce the link's cost by factor R
1318
Have all the remaining links been processed?
1314
No
Yes
Select the next of the remaining links
1316
Using the remaining links and new link costs calculate a minimum cost restoration path for the primary path
1320
Exit
1322

FIG. 13

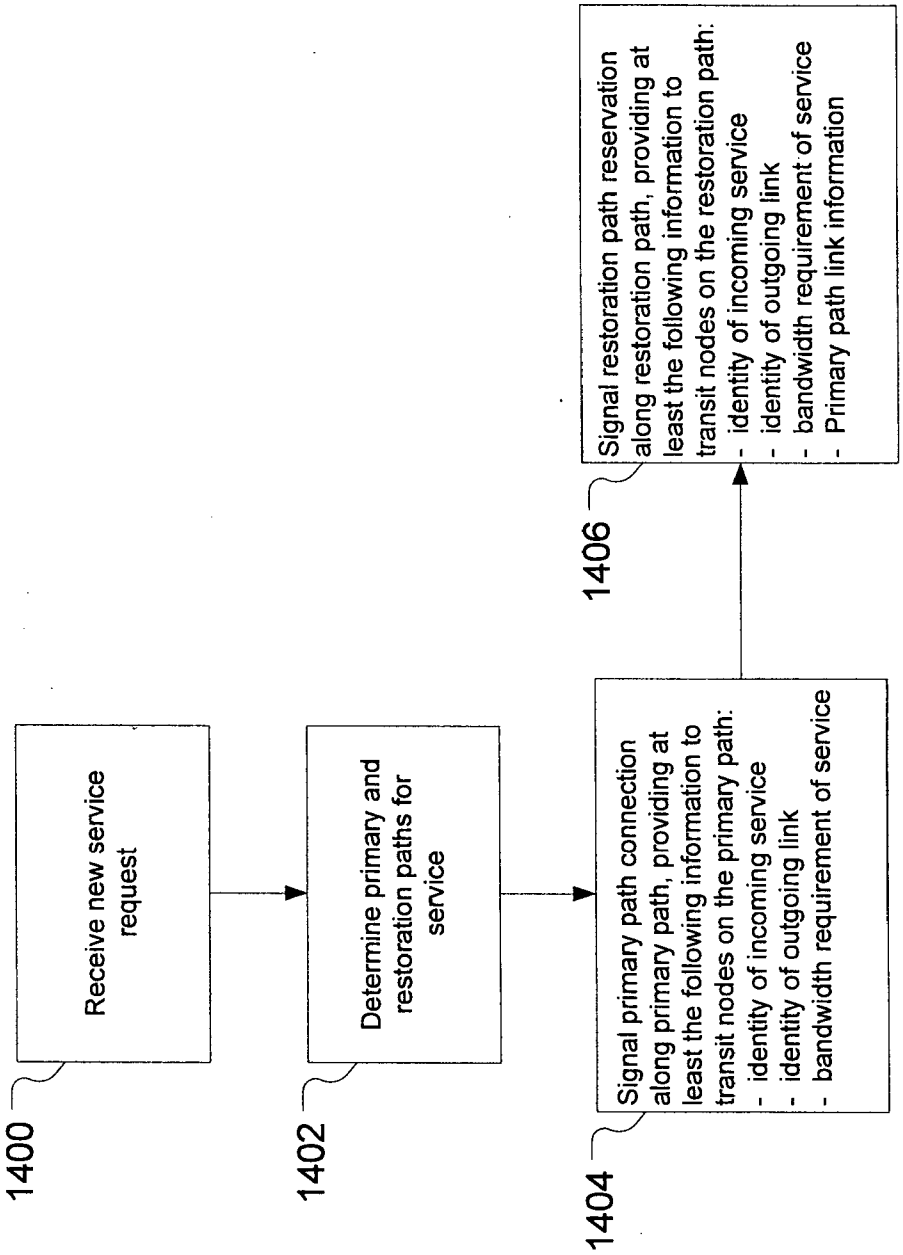

1400
Receive new service request
1402
Determine primary and restoration paths for service
1404
Signal primary path connection along primary path, providing at least the following information to transit nodes on the primary path:
- identity of incoming service
- identity of outgoing link
- bandwidth requirement of service
1406
Signal restoration path reservation along restoration path, providing at least the following information to transit nodes on the restoration path:
- identity of incoming service
- identity of outgoing link
- bandwidth requirement of service
- Primary path link information

FIG. 14

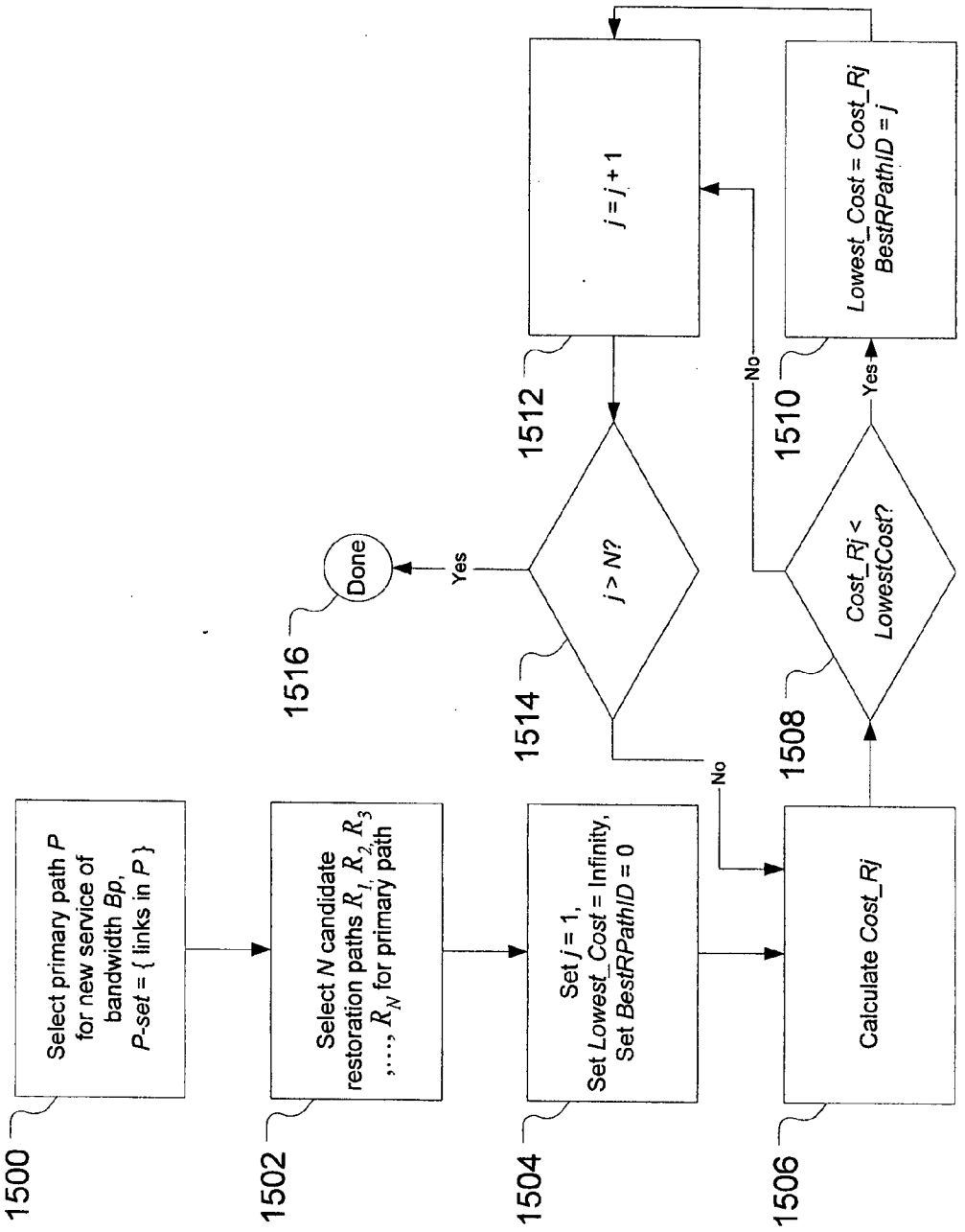

1500
Select primary path P for new service of bandwidth Bp, P-set = { links in P }
1502
Select N candidate restoration paths R1, R2, R3 , ..., RN for primary path
1504
Set j = 1, Set Lowest_Cost = Infinity, Set BestRPathID = 0
1506
Calculate Cost_Rj
1508
Cost_Rj < LowestCost?
Yes
No
1510
Lowest_Cost = Cost_Rj BestRPathID = j
1512
j = j + 1
1514
j > N?
Yes
No
1516
Done

FIG. 15

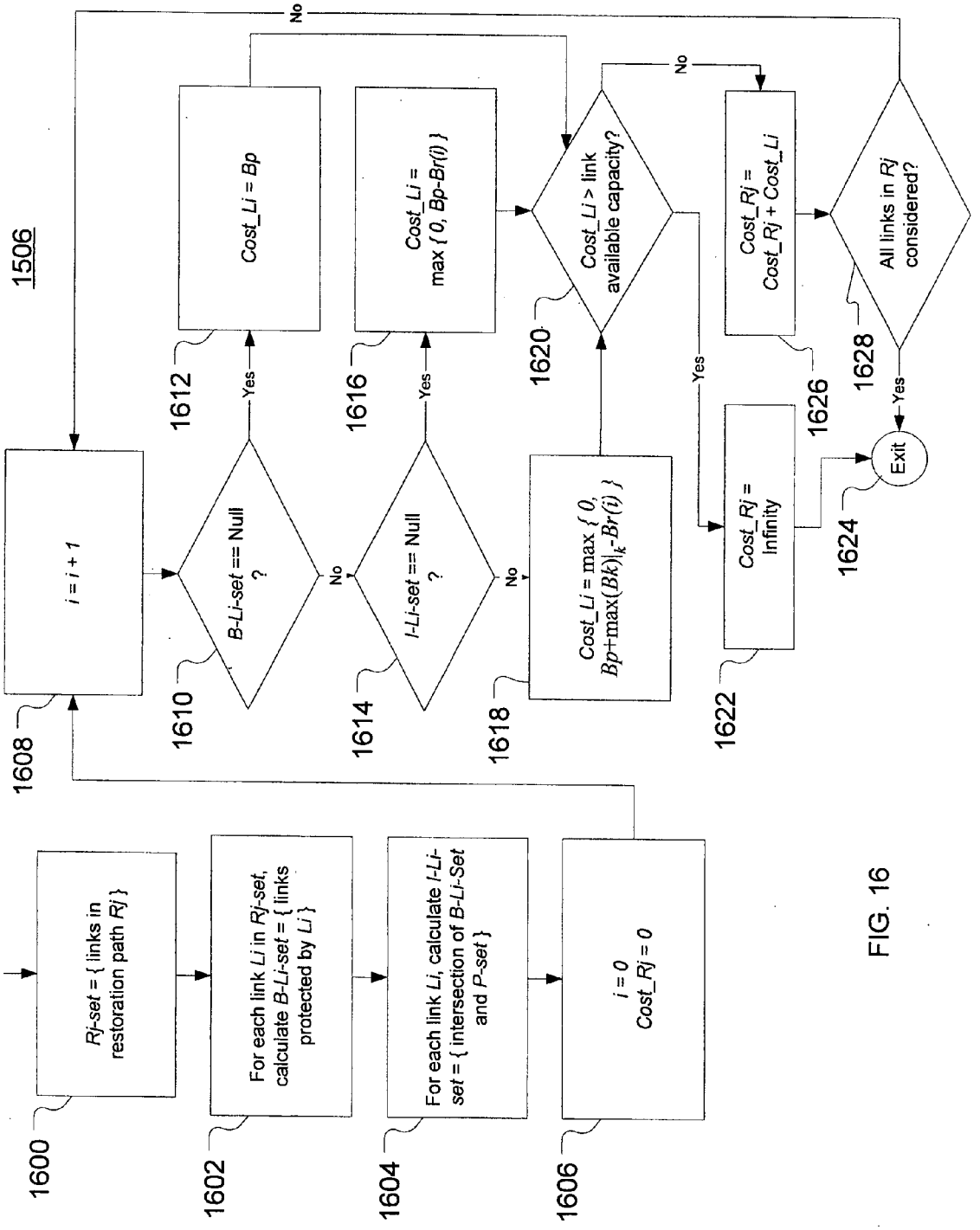

1506
Rj-set = { links in restoration path Rj }
1600
For each link Li in Rj-set, calculate B-Li-set = { links protected by Li }
1602
For each link Li, calculate I-Li-set = { intersection of B-Li-Set and P-set }
1604
i = 0
Cost_Rj = 0
1606
i = i + 1
1608
B-Li-set == Null ?
1610
Yes
No
Cost_Li = Bp
1612
I-Li-set == Null ?
1614
Yes
No
Cost_Li = max { 0, Bp-Br(i) }
1616
Cost_Li = max { 0, Bp+max(Bk)|k-Br(i) }
1618
Cost_Li > link available capacity?
1620
Yes
No
Cost_Rj = Infinity
1622
Cost_Rj = Cost_Rj + Cost_Li
1626
All links in Rj considered?
1628
Yes
No
Exit
1624

FIG. 16

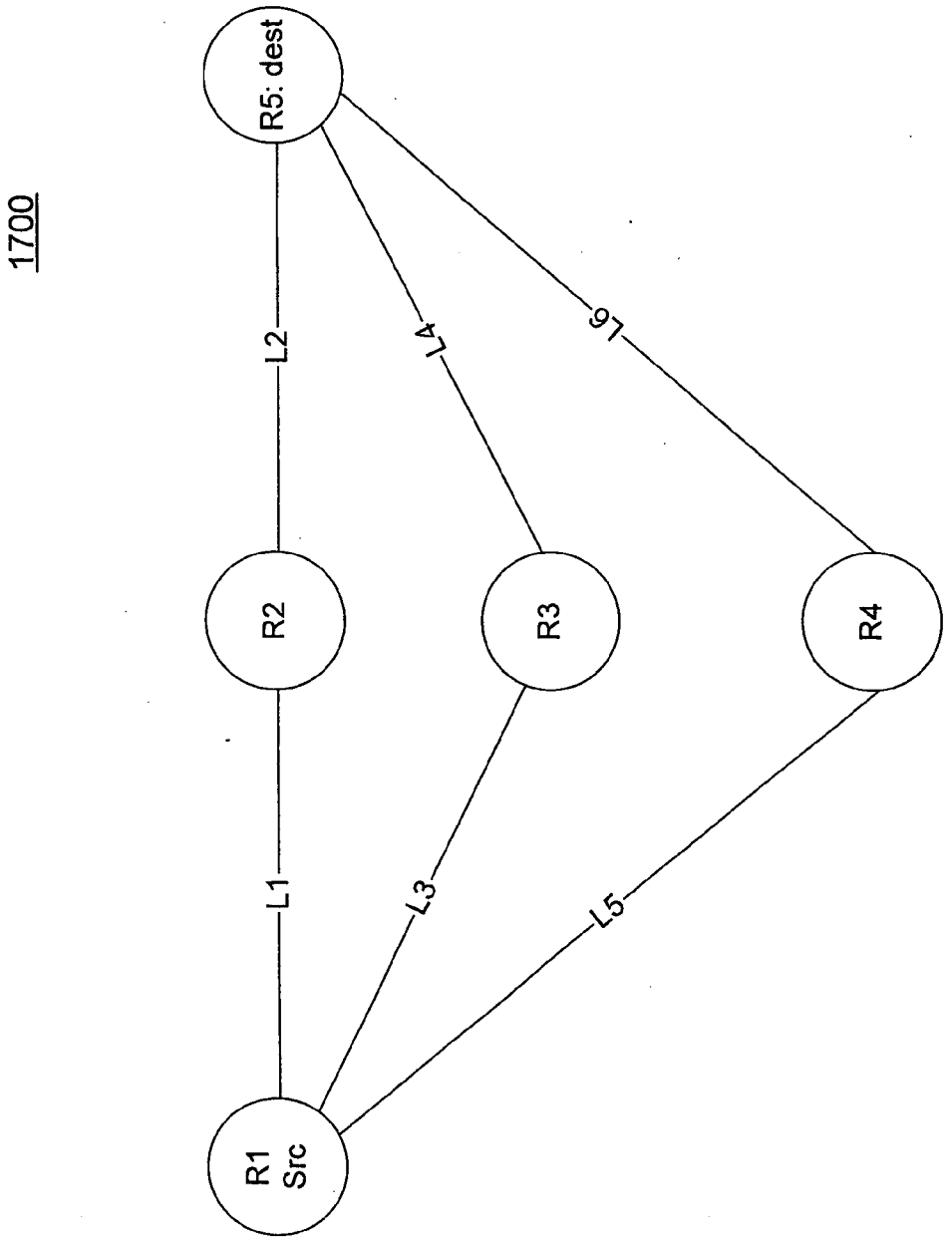


FIG. 17

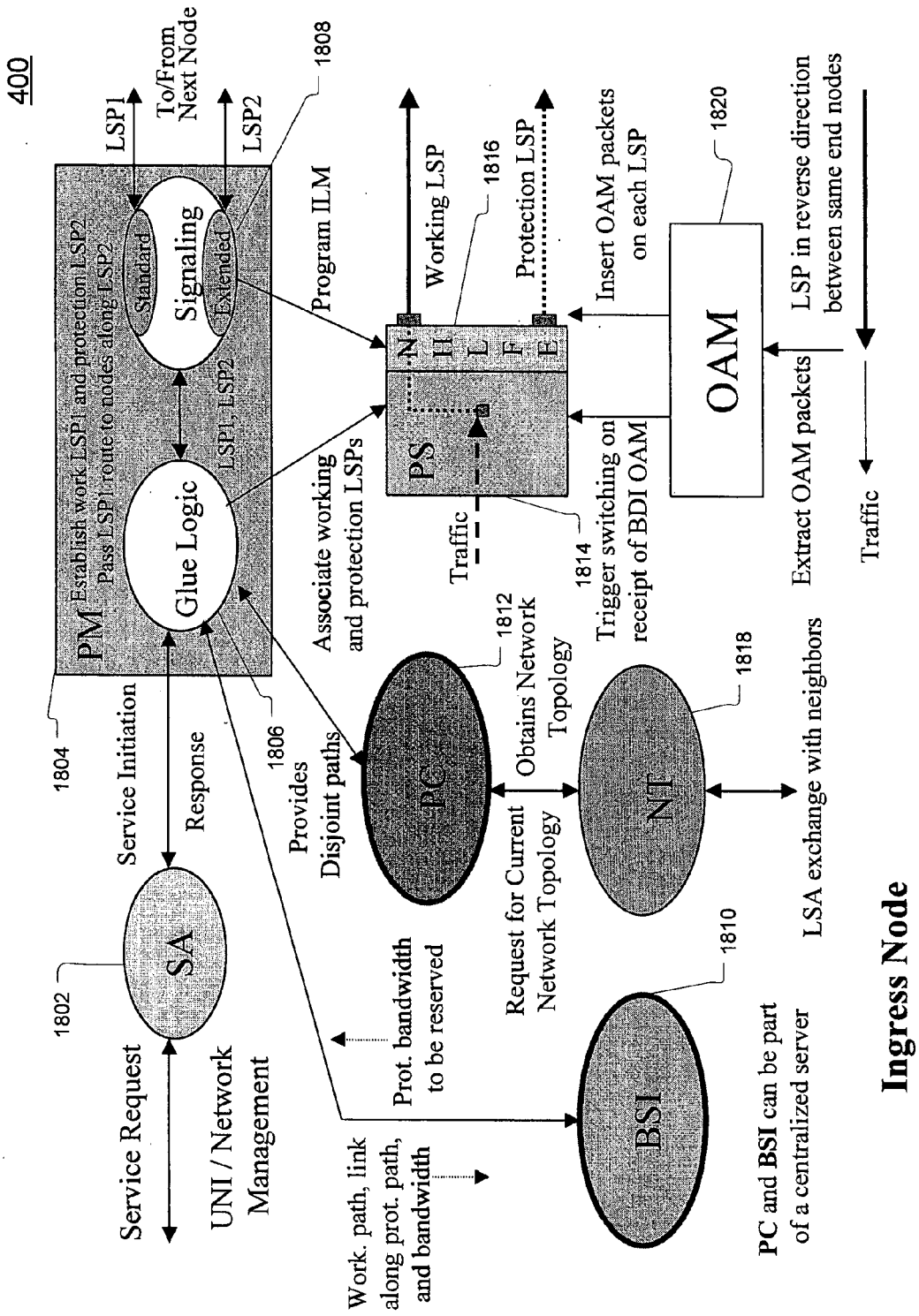

400
PM
Establish work. LSP1 and protection LSP2
Pass LSP1 route to nodes along LSP2
Standard
Signaling
Extended
Glue Logic
LSP1 - LSP2
LSP1
To/From Next Node
LSP2
1808
1804
1806
Service Initiation
Response
SA
1802
Service Request
UNI / Network Management
Program ILM
Associate working and protection LSPs
Provides Disjoint paths
PC
1812
Obtains Network Topology
Request for Current Network Topology
NT
1818
LSA exchange with neighbors
Prot. bandwidth to be reserved
Work. path, link along prot. path, and bandwidth
BSI
1810
PC and BSI can be part of a centralized server
Ingress Node
PS
N
H
L
F
E
Traffic
1814
Trigger switching on receipt of BDI OAM
Working LSP
1816
Protection LSP
Insert OAM packets on each LSP
OAM
1820
Extract OAM packets
LSP in reverse direction between same end nodes
Traffic

FIG. 18

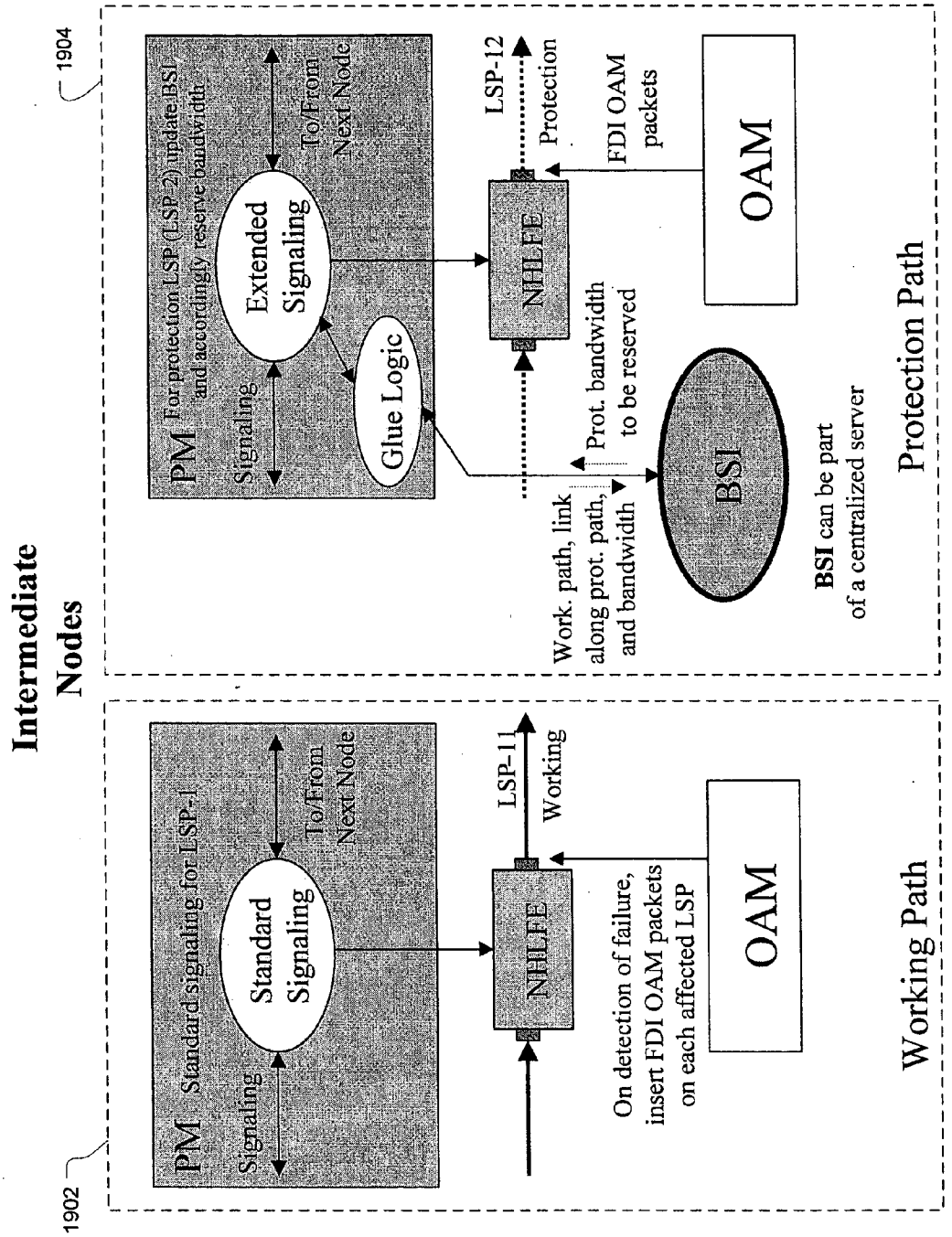

Intermediate Nodes
1904
PM For protection LSP (LSP-2) update BSI and accordingly reserve bandwidth
Signaling
Extended Signaling
To/From Next Node
Glue Logic
NHLFE
LSP-12
Protection
FDI OAM packets
OAM
Prot. bandwidth to be reserved
Work. path, link along prot. path, and bandwidth
BSI
BSI can be part of a centralized server
Protection Path
1902
PM Standard signaling for LSP-1
Signaling
Standard Signaling
To/From Next Node
NHLFE
LSP-11
Working
On detection of failure, insert FDI OAM packets on each affected LSP
OAM
Working Path

FIG.19

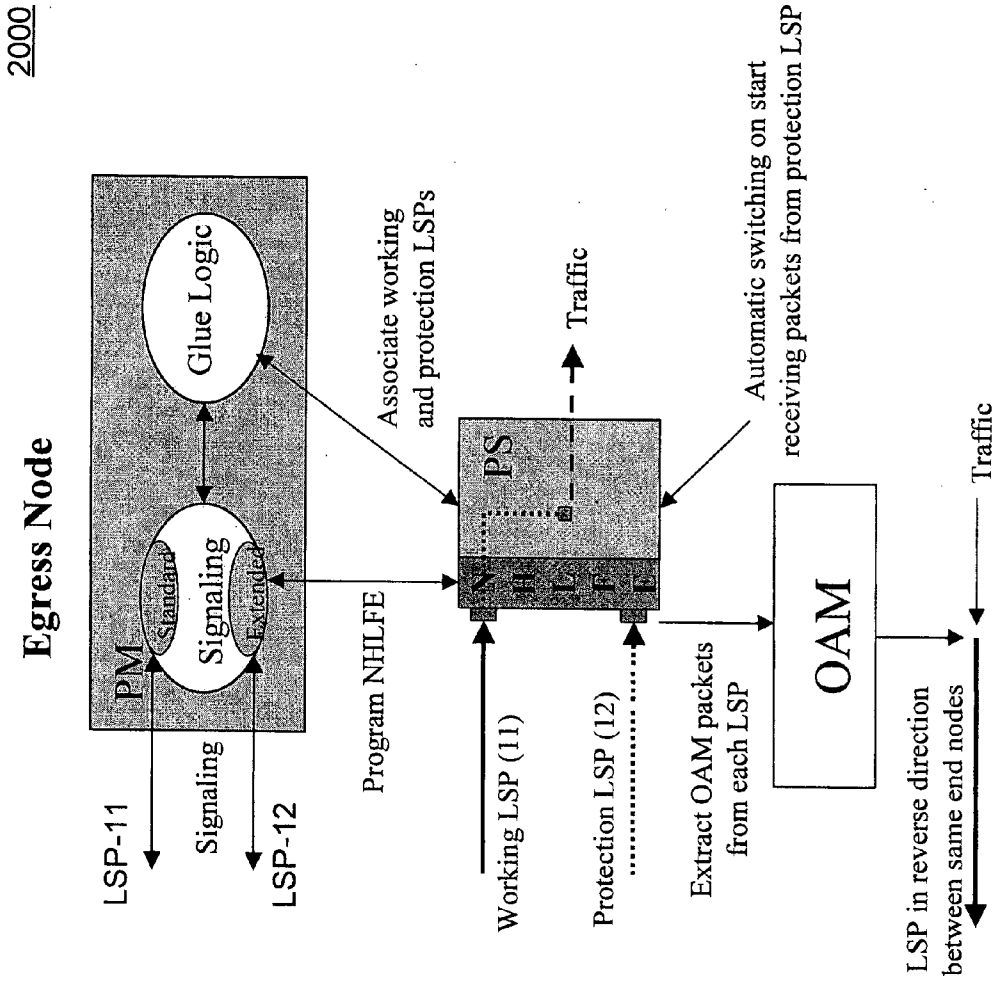

2000
Egress Node
PM
Standard
Signaling
Extended
Glue Logic
LSP-11
Signaling
LSP-12
Program NHLFE
Associate working and protection LSPs
PS
N
H
L
F
E
Traffic
Working LSP (11)
Protection LSP (12)
Automatic switching on start receiving packets from protection LSP
Extract OAM packets from each LSP
OAM
LSP in reverse direction between same end nodes
Traffic

FIG. 20

PRIMARY/RESTORATION PATH CALCULATION IN MESH NETWORKS BASED ON MULTIPLE-COST CRITERIA

CROSS-REFERENCE TO RELATED APPLICATIONS

[0001] This application claims the benefit of the filing date of U.S. provisional application No. 60/459,163, filed on Mar. 31, 2003. The subject matter of this application is related to U.S. patent application Ser. No. 10/639,728, filed on Aug. 12, 2003 as attorney docket no. Dziong 8-25-16-32, the teachings of which are incorporated herein by reference.

[0002] This application is one of a set of U.S. patent applications consisting of Ser. No. 10/_____ filed as attorney docket no. Doshi 56-5-21-17-33, Ser. No. 10/_____ filed as attorney docket no. Doshi 57-6-22-18-34, Ser. No. 10/_____ filed as attorney docket no. Doshi 55-7-23-15-35, Ser. No. 10/_____ filed as attorney docket no. Dziong 9-1, and Ser. No. 10/_____ filed as attorney docket no. Doshi 58-10-27-19-36, all of which were filed on the same date and the teachings of all of which are incorporated herein by reference.

BACKGROUND OF THE INVENTION

[0003] 1. Field of the Invention

[0004] The present invention relates to network communications and, more specifically, to restoration path sharing.

[0005] 2. Description of the Related Art

[0006] Advances in wavelength-division multiplexing (WDM) related technologies have started to allow for routing and networking at the optical layer (e.g., optical switch layer) of communications networks, providing a migration toward true optical-layer networking. Optical-layer networking associated with mesh-connected optical networks creates the need for routing wavelength demands over the mesh optical networks and an equivalent need for service recovery in the optical domain in the event of failures.

[0007] Traditionally, the optical-layer network provided for fast recovery services, while data networks (e.g., Internet Protocol (IP) networks) were primarily targeted to achieve "best-effort" services. However, with the increasing use of data networks to carry time-critical data (e.g., voice-over-IP (VOIP) data), resiliency and fast recovery of service are becoming important features of data networks as well. Advances in traffic engineering of data networks, such as those covered under the umbrella of multiprotocol label switching (MPLS), have provided a framework for directing the flow of specific services within IP networks.

[0008] For both optical-layer networking applications and data networking applications, distribution of topology information, and, in particular, restoration, recovery, and sharing information, is important to the efficient and timely recovery of services. However, many of the restoration and recovery schemes in the prior art fail to provide a compact representation of the relevant information, methods to utilize the data in path calculations in consideration of multiple cost criteria in a way that benefit from sharing of protection link resources, and efficient, distributed mechanisms for making that data available where and when it is needed.

SUMMARY OF THE INVENTION

[0009] Problems in the prior art are addressed in accordance with principles of the present invention by a shared mesh network (SMN) that includes components for compact representation and maintenance of network sharing information, dissemination of the sharing information within the network, and improved service primary and restoration path calculation as a function of the sharing information.

[0010] In one embodiment, the SMN is an IP network, and sharing components include extensions to the multiprotocol label switching (MPLS) traffic engineering specifications, specifically, open shortest path first with traffic engineering extensions (OSPF-TE) and OSPF opaque link-state advertisement option.

[0011] The SMN includes components that determine primary/restoration path pairs in consideration of the grouping of certain links within the network into shared-risk link groups (SRLGs). Links that belong to SRLGs having a primary path link, are set to a link cost of infinity, while the remaining links that do not belong to such SRLGs are evaluated as to their ability to support sharing of restoration bandwidth. If a link supports sharing, its link cost is reduced by a factor R. This factor R can be a function of the sharing degree for the link as discussed previously. Ultimately, the adjusted link costs are used in a minimum-cost primary/restoration path calculation.

[0012] Components of the SMN distribute an accurate but optimized link state description in the form of an integer node-link or node vectors. The SMN features path-based recovery providing efficient sharing of protection capacity, while putting few requirements on intermediate network elements. The SMN includes mechanisms for fast detection, fast failure notification, signaling to enable protection and bandwidth sharing, and identification of locally cached vs. transmitted sharing information. Although not limited to optical applications, the present invention can be implemented in communication networks that transmit signals between nodes using optical transmission technology.

[0013] In one possible implementation, the shared mesh network includes (a) two or more nodes, (b) two or more optical links interconnecting the nodes, (c) a network manager (either centralized or distributed) adapted to control reservation of protection bandwidth for the links, and (d) components for calculating and updating sharing information. In this implementation, a first link in the network is part of two or more different protection paths, where each protection path corresponds to a different primary path. The network manager makes use of the sharing information to determine how much protection bandwidth to reserve on the first link for the two or more protection paths in such a way that the protection bandwidth reserved on the first link is shared between the protection paths of the two or more primary paths. As such, the amount of protection bandwidth reserved on the first link can be less than the sum of the bandwidths of the two or more primary paths.

[0014] In one embodiment, the invention is a method for determining primary and restoration paths for a new service in a mesh network having a plurality of nodes interconnected by a plurality of links. For each of a plurality of candidate path pairs for the new service, each candidate path pair comprising a candidate primary path and a candidate

restoration path for the new service, a path cost associated with said each candidate path pair is generated, wherein the path cost for a candidate path pair is a function of sharability of links within the corresponding candidate restoration path. The primary and restoration paths for the new service are selected from the plurality of candidate path pairs based on the path cost of each candidate path pair. The method may be implemented by a network manager for the mesh network.

BRIEF DESCRIPTION OF THE DRAWINGS

[0015] Other aspects, features, and advantages of the present invention will become more fully apparent from the following detailed description, the appended claims, and the accompanying drawings in which:

[0016] **FIG. 1** illustrates an exemplary shared mesh data network (SMDN) according to one embodiment of this invention.

[0017] **FIG. 2** illustrates TABLE **1**, which captures an example of the amount of restoration capacity required on each link for recovering from every possible single link or node failure in the SMDN of **FIG. 1**.

[0018] **FIG. 3** illustrates TABLE **2**, which captures an example of the amount of restoration capacity required on each link for every possible single link or node failure in the SMDN of **FIG. 1** after the restoration capacity required to protect an additional primary path has been added to already allocated restoration capacity of TABLE **1**.

[0019] **FIG. 4** depicts an exemplary restoration message processing method for source nodes and transit nodes in a mesh network.

[0020] **FIG. 5** depicts an exemplary shared mesh data network supporting multiple services via disjoint primary and restoration paths.

[0021] **FIG. 6** depicts node-link aggregate vector and node-aggregate vector representations of sharing information.

[0022] **FIG. 7** depicts node-link binary vector and node-binary vector representations of sharing information.

[0023] **FIG. 8** depicts the exemplary shared mesh data network of **FIG. 5** with an additional service added.

[0024] **FIG. 9** depicts the primary path node-link vector representation and the primary path node-vector representation of the new primary path in the network of **FIG. 8**.

[0025] **FIG. 10** illustrates a routine for calculating the link cost as a function of sharing and link utilization.

[0026] **FIG. 11** depicts an exemplary method for calculating a minimum-cost primary/restoration path pair for a new service in consideration of link utilization, utilization threshold, administrative weight, and sharing degree.

[0027] **FIG. 12** illustrates one exemplary method for calculating primary and restoration paths that takes into account bandwidth sharing for restoration paths and considers the impact of shared-risk link groups (SRLGs).

[0028] **FIG. 13** illustrates an exemplary approach to implementing step **1206** of the method of **FIG. 12**.

[0029] **FIG. 14** illustrates an exemplary connection setup procedure extension to support sharing in mesh networks.

[0030] **FIG. 15** illustrates an exemplary procedure for determining a minimum-cost restoration path given a particular primary path.

[0031] **FIG. 16** illustrates an exemplary procedure for calculating the cost of each restoration path Rj per step **1506** of **FIG. 15**.

[0032] **FIG. 17** illustrates a portion of a mesh network.

[0033] **FIG. 18** illustrates exemplary modules, representing one specific functional partitioning of components of an ingress node of the SMDN of **FIG. 1**.

[0034] **FIG. 19** illustrates exemplary modules included in intermediate nodes along a working path and a protection path of the SMDN of **FIG. 1**.

[0035] **FIG. 20** illustrates exemplary modules, representing one specific functional partitioning of components of an egress node of the SMDN of **FIG. 1**.

DETAILED DESCRIPTION

[0036] Reference herein to "one embodiment" or "an embodiment" means that a particular feature, structure, or characteristic described in connection with the embodiment can be included in at least one embodiment of the invention. The appearances of the phrase "in one embodiment" in various places in the specification are not necessarily all referring to the same embodiment, nor are separate or alternative embodiments mutually exclusive of other embodiments.

[0037] Introduction

[0038] Significant research has been done into various restoration and protection strategies for mesh networks at both the packet and optical layers. Proposed architectures include centralized vs. distributed, pre-computed vs. computed on demand in real-time, and link-based vs. path-based. Characteristics that distinguish between these various restoration and protection strategies include recovery time, failure coverage, and required recovery capacity. A survey of relevant research as well as a specific distributed recovery strategy that provides sub-second recovery times for carrier-scale mesh-based optical networks is addressed in Doshi, B. T., Dravida, S., Harshavardhana, P., Hauser, O., and Wang, Y., "Optical Network Design and Restoration," Bell Labs Technical Journal, January-March 1999 (herein "Doshi '99"), incorporated herein by reference in its entirety.

[0039] So-called "shared mesh recovery" is a known concept in optical transport networks (e.g., SONET/SDH). In this scheme, when a failure occurs, the network recovers service carried by the affected paths by using recovery capacity that has been set aside on alternative routes for this purpose. The recovery capacity can be shared over multiple failure scenarios. This involves commensurate switching capability from the transport network elements (e.g., digital cross connects).

[0040] For both optical-layer networking applications and data networking applications, resiliency requires extra capacity in the network sufficient to recover from any network failures such as fiber cable cuts or network element failures. This extra capacity is commonly known as the

restoration capacity. Normally the extra capacity is sized for recovering from only a single failure at a given time in the network. This is due to the fact that the probability of occurrence of more than one failure during the time interval required to repair a failure is very insignificant, and therefore most of the time it is sufficient to cover just a single network failure. This also provides opportunity to share restoration capacity between disjoint network failures. To understand sharing, realize that if two primary paths carrying traffic are routed disjointly, then a failure affecting one of them will not affect the other. Now, if the corresponding protection paths are routed such that they share common links then the restoration capacity on those links can be shared for restoring traffic between any failures along their primary routes. In general, sharing can be achieved by:

[**0041**] 1) realizing primary paths which do not share one or more links along their routes,

[**0042**] 2) realizing the links that are common along their restoration paths, and

[**0043**] 3) sharing the restoration capacity on these common links across the failure of any disjoint links along their primary routes.

[**0044**] Fast and guaranteed recovery requires that restoration paths need to be computed in advance of any failure and accordingly, restoration capacity needs to be set aside. Efficient use of restoration capacity can be achieved using sharing. Sharing can be achieved by realizing at each link along the restoration path the amount of restoration capacity required to recover from each failure (link or node) in the network and then comparing it with the primary path information for estimating any possible sharing (i.e., the amount of already allocated restoration capacity that can be used for protecting the primary path from a failure along its route). In the case of a centralized implementation, all this information is available at the server. Whereas, in case of a distributed implementation, each node keeps track of the sharing details for each connected link in the downstream direction. This information can be built by passing the primary path information to each node along the protection path.

[**0045**] Sharing information enables computation of more efficient primary and secondary paths. This suggests that when a node that is responsible for computing primary and secondary paths is aware of the sharing information (for a distributed implementation the information is distributed across the nodes in the network), it will be able to compute more efficient paths. Thus, for a distributed implementation, it is desirable to distribute the sharing information at each node across the network. Usually the distribution of sharing information across the network is a costly operation. Therefore, it is highly useful to abstract the most useful information and represent it in a compact form for distribution. A link-state routing protocol (such as OSPF), which already disseminates topology information, can be used to distribute the sharing information.

[**0046**] Unless otherwise clear from the context, the process of "restoration" is synonymous in this specification with the process of "protection." In general, such process involves various associated recovery actions following the detection of a failure, including switching to an alternative (i.e., restoration) path. Depending on the implementation, such process may involve either pre-computation or real-time computation of alternative paths. Pre-computation generally exhibits shorter recovery times but maybe less optimal than real-time computation, which benefits from the ability to take into account the most current state of the network demands and resources. Also depending on the implementation, such process may involve either pre-allocation or real-time allocation of bandwidth on alternative paths. Pre-allocation generally exhibits shorter recovery times but may be less desirable than real-time allocation as the former requires the use of the bandwidth even in the absence of a fault for which it is reserved, while the latter leaves the bandwidth available for opportunistic services that do not have a guaranteed quality of service. Also, depending on the implementation, such process may involve either pre-establishment or real-time establishment of alternative paths. Pre-establishment generally exhibits shorter recovery times than real-time establishment and is preferred if it is supported by the network elements.

[**0047**] The Shared Mesh Data Network

[**0048**] **FIG. 1** illustrates an exemplary shared mesh data network (SMDN) **100** according to one embodiment of this invention. A mesh network is a network topology (or a subset thereof) in which there are at least two nodes having two or more paths between them. A path is a set of one or more links and zero, one, or more corresponding intermediate nodes that interconnect links. As shown, SMDN **100** includes six ingress/egress nodes **N1** to **N6** interconnected by seven bidirectional links **L1** to **L7**. These nodes and links provide different paths between different pairs of nodes. For example, links **L2**, **L5**, and **L7** and nodes **N2** and **N3** provide a path between nodes **N1** and **N6**. Similarly, links **L2**, **L4**, and **L6** and nodes **N2** and **N5** provide another path between nodes **N1** and **N6**.

[**0049**] The concepts of the present invention are discussed in the context of exemplary shared mesh data networks. However, without loss of generality, they may be applied generally to any mesh network (e.g., Sonet, ATM, frame relay, MPLS) that provides traffic-switching control at the nodes incident to the links in the network. A mesh data network is a network in which data is communicated asynchronously between nodes in packetized form and it is a specific case of the more general mesh network. In the present example, SMDN **100** supports the multiprotocol label switching (MPLS) architecture standard per Rosen, E., et al., "RFC3031—Multiprotocol Label Switching Architecture," Network Working Group, The Internet Society, January 2001, incorporated herein by reference in its entirety; however, as would be understood by one skilled in the art, other data technologies that offer similar data traffic engineering features (e.g., ATM and frame relay) could be substituted for MPLS.

[**0050**] As illustrated, SMDN **100** has been provisioned with five primary label-switched paths (LSPs) LSP-**1** to LSP-**5**. A label-switched path is effectively a tunnel between two nodes that carries service traffic according to a predetermined route. For example, LSP-**1** is a tunnel from node **N3** to node **N5** that follows the path **N3**-**N2**-**N5**. (LSP-**1** could alternatively be described by the links it traverses, i.e., **L5**-**L4**, or by the nodes and links, i.e., **N3**-**L5**-**N2**-**L4**-**N5**; however, for this discussion, in cases where no ambiguity will arise from the node-only notation, that notation will be used.)

[0051] An LSP is typically considered to be unidirectional; however, for clarity of illustration, each LSP in **FIG. 1** is represented by a bidirectional path that could also represent the corresponding unidirectional LSP in the opposite direction. Further, each LSP may have an associated demand of any reasonable value (e.g., 2Mbps, 10 Mbps, and 100 Mbps); however, without loss of generality, for this example, each of the LSPs in **FIG. 1** is assumed to be of unit demand. Extensions to pairs of unidirectional LSPs and variable demands would be understood to one skilled in the art.

[0052] **FIG. 1** illustrates the five primary LSPs as follows: LSP-**1** carries traffic along path N**3**-N**2**-N**5**, LSP-**2** carries traffic along path N**4**-N**5**-N**6**, LSP-**3** carries traffic along path N**2**-N**1**-N**4**, LSP-**4** carries traffic along path N**2**-N**5**, and LSP-**5** carries traffic along path N**2**-N**3**-N**6**.

[0053] Disjoint Primary and Protection Paths

[0054] **FIG. 1** also illustrates five exemplary protection paths LSP-**6** to LSP-**10** (also of unit bandwidth in this example) that have been reserved to use for protection of services given a failure of one of the primary paths. LSP-**6** (along path N**3**-N**6**-N**5**) protects LSP-**1**, LSP-**7** (along path N**4**-N**1**-N**2**-N**3**-N**6**) protects LSP-**2**, LSP-**8** (along path N**2**-N**5**-N**4**) protects LSP-**3**, LSP-**9** (along path N**2**-N**1**-N**4**-N**5**) protects LSP-**4**, and LSP-**10** (along path N**2**-N**5**-N**6**) protects LSP-**5**. For clarity, in **FIG. 1**, the tag for each protection LSP carries a parenthetical suffix indicating the primary LSP it protects. For example, LSP-**6** (P**1**) indicates the protection role that LSP-**6** plays for primary LSP-**1**.

[0055] Note that the protection paths in the example of **FIG. 1** are strictly disjoint from the primary paths that they protect. In this context, strictly disjoint means that the two paths in each primary/protection path pair share no common links or nodes other than their common ingress and egress nodes. Though the protection paths of this example are strictly disjoint from the paths they protect, this need not be the case in all implementations of the present invention. There will be some cases in some variants of the invention where no strictly disjoint path exists between two nodes to serve as a protection path. In other cases, other factors or constraints of the routing algorithm may lead to selection of a protection path, for a given primary path, that is not strictly disjoint from the primary path (e.g., the protection path may share some common links with the primary path). Thus, rather than being limited to strictly disjoint, the primary paths in embodiments of this invention are at least partially disjoint from their respective protection paths, where two partially disjoint paths have at least two links that are different. With this definition, a strictly disjoint path is a particular type of partially disjoint path.

[0056] A number of different mechanisms exist in the art for determination of disjoint paths between nodes given various topology and traffic information. Some exemplary algorithms are detailed in Doshi '99. Additionally, mechanisms exist for establishing primary and protection LSPs, once they are determined, e.g., simple network management protocol (SNMP) per Network Working Group, "Introduction to a Simple Network Management Protocol (SNMP) version 3, " RFC2570, April 1999 (herein "RFC2570") and RSVP-TE as covered by Awduche, D., Berger, L., Gan, D., et al., "RSVP-TE: Extensions to RSVP for LSP Tunnels," RFC 3209, December 2001 (herein "RFC 3209"), each of which is incorporated herein by reference in its entirety.

[0057] Link Capacity

[0058] In the embodiment of the invention illustrated by the example of **FIG. 1**, to provide for full recovery of services given any single-link failure, the capacity of a link must be large enough to accommodate the primary services that it supports as well as the services it protects. For example, L**5** is one link in primary service paths LSP-**1** and LSP-**5**. It is said to "support" both of those paths. Assuming that LSP-**1** and LSP-**5** each carry one unit of demand bandwidth, L**5** will need at least two units of allocated capacity to support those two paths. L**5** is also part of the protection path (LSP-**7**) for service path LSP-**2** (requiring an additional one unit of capacity). Thus, in this example, the capacity of L**5** must be at least three units of bandwidth: two units of allocated bandwidth and one unit of reserved bandwidth.

[0059] Reservation vs. Allocation

[0060] In one embodiment of the present invention, the bandwidth associated with the protection path (LSP-**7**) for service path LSP-**2** is not allocated in advance of a failure, but is, instead, only reserved. If the bandwidth were allocated in advance of a failure, this would correspond, in the parlance of the field of protection and restoration for optical transport networks, to a 1:1 protection scheme. If the bandwidth were not only allocated, but additionally if a copy of the service path's data were to be duplicated to the protection path, this would correspond to a 1+1 protection scheme. However, in preferred embodiments of this invention, the protection bandwidth is not allocated until after the detection of a failure. Thus, in such implementations, this unallocated bandwidth might be used for "opportunistic" data, e.g., data that has a lower guaranteed quality of service (QoS) than the protected traffic. Further, because the protection bandwidth is only reserved and not allocated, "sharing" can be supported, as defined below.

[0061] Sharing and Single Failure Coverage

[0062] Another characteristic of certain networks of this invention is termed "sharing." This refers to the facility to share reserved protection capacity on a link between more than one LSP. As described previously, the primary paths provisioned on the SMDN are assumed to be at least partially disjoint from their respective protection paths. This means that, for at least one link in each primary path, there is a detour segment in the corresponding protection path that has been designated to carry reserve capacity to protect the primary path. Recovery from a failure of a link along a primary path that has a corresponding detour segment in the protection path is achieved by switching the affected traffic at the ingress node from the failed primary path to the corresponding protection path. For a successful recovery, at the time of protection switching, enough capacity should be available on all links along the protection path. One way of achieving this is by allocating dedicated bandwidth along the protection path of each LSP. This will result in excessive use of protection bandwidth. A more efficient scheme involves sharing the protection capacity of a link between LSPs that are not generally affected by the same single node or link failure.

[0063] For example, consider the protection capacity that is set aside (i.e., reserved) on a link along the protection path to recover from a failure along a first primary path. Next

assume that this link is also designated as part of the protection path of a second primary path that is disjoint from the first primary path (in this case, the second primary path would not be affected by a failure along the first primary path). Then, given the assumption that no more than one link will fail at a given point in time (a reasonable assumption given the mean-time-between-failure (MTBF) statistics of state-of-the-art networks), the two primary paths may "share" the reserved protection bandwidth of the protection link.

[**0064**] An example should help clarify the concept. Consider LSP-**3** of SMDN **100** as the first primary path. It is protected by LSP-**8**, which includes L**4** (i.e., LA is a protection link for LSP-**3**). L**4** also serves as part of the protection path (LSP-**10**) of LSP-**5**, where LSP-**5** does not share any links with LSP-**3** (i.e., LSP-**3** and LSP-**5** are disjoint). Thus, only one unit of capacity needs to be reserved on L**4** to protect against a failure affecting either LSP-**3** or LSP-**5**. LSP-**3** and LSP-**5** are considered to "share" this protection capacity on L**4**. The extension of this concept to the full SMDN is considered to be a generalized shared mesh technique. Node failures represent another basis for protection bandwidth reservation and may similarly benefit from sharing.

[**0065**] Worst-Case Link Protection Capacity

[**0066**] The amount of bandwidth reserved on a given link for protection purposes is chosen to accommodate the worst-case traffic demand that would be placed upon that link given the failure of any other one link or any one node in the network. As another example of sharing and to help clarify this concept, consider link L**6** of SMDN **100**.

[**0067**] Link L**6** supports both LSP-**6** and LSP-**10**, the protection paths for LSP-**1** and LSP-**5**, respectively. LSP-**1** includes intermediate node N**2** and links L**4** and L**5**, while LSP-**5** includes intermediate node N**3** and links L**5** and L**7**. Since N**2** is a terminal node of LSP-**5**, service protection for LSP-**5** is not available in the event of a failure of N**2**. As such, only one unit of reserve capacity on link L**6** is needed to protect LSP-**1** from a failure of N**2**. Similarly, since N**3** is a terminal node of LSP-**1**, service protection for LSP-**1** is not available in the event of a failure of N**3**. As such, only one unit of reserve capacity on link L**6** is needed to protect LSP-**5** from a failure of N**3**. A failure of link L**4** would result in a failure of LSP-**1**, creating a need for one unit of reserve capacity on link L**6**. Similarly, a failure of link L**7** would result in a failure of LSP-**5**, also creating a need for one unit of reserve capacity on link L**6**. Since L**4** and L**7** are independent links, a failure of only one or the other (but not both) is all that needs to be considered. Thus, the reserve capacity required on L**6** could still be capped at one unit.

[**0068**] However, if a failure on L**5** is considered, both LSP-**1** and LSP-**5** are affected. Since this one failure could result in a concurrent demand of two, a "worst case" of two units of bandwidth would have to be reserved on L**6** to ensure maximal recovery of the network under the assumption of a maximum of one link or node failure at time. In general, in the calculation of the reserve capacity required for each link of SMDN **100**, the effect of the failure of each node and each of the other links in the network is independently considered and the worst-case capacity is reserved.

[**0069**] Tabulation The concepts of the previous sections are quantified by TABLE **1** of **FIG. 2**. TABLE 1 shows the amount of protection capacity required on each link for recovering from every possible single link or node failure in SMDN **100** of **FIG. 1**. Each row of TABLE **1** corresponds to a different link of SMDN **100**. For each row (corresponding to a particular link), each column entry identifies the protection capacity for that link in order to protect service in the event of a failure of the link or node associated with that column in the table. Using a table such as TABLE **1**, the sharing of protection capacity between different failures can be realized.

[**0070**] To better understand TABLE **1**, consider the first row, which is associated with link L**1**. The entry of "1" in the column labeled L**3** for the first row indicates that there is one unit of traffic on link L**3** (due to LSP-**2**) that would employ link L**1** on its recovery route if link L**3** gets impacted by a failure. Similarly, the entry of "1" in the column labeled N**5** addresses the case of a failure of node N**5** and its impact on link L**1**. The last column titled Max is the maximum value of all entries in that row. It is the amount of protection bandwidth that needs to be reserved on that link for the worst-case single failure in the network. This value for link L**6**, for example, is 2 units to cover the case of a failure of link L**5** as discussed in the previous section (and as reflected by the entry of "2" in row L**6**, column L**5** of TABLE **1**). The other entries of TABLE **1** are determined similarly.

[**0071**] Completion of the information in TABLE **1** and the calculation of the Max value enable the determination of how much protection capacity to reserve on each link in the SMDN to realize full recovery of services in the SMDN in the event of a single link or node failure.

[**0072**] Distributed vs. Centralized Sharing Database

[**0073**] The information in TABLE **1** can be either maintained in a centralized fashion at a server or distributed to the nodes in the SMDN. In case of a centralized architecture, TABLE **1** might reside on a centralized server and be updated after the provisioning of each new primary and protection LSP. Signaling could be used to notify nodes of any change in the reservation bandwidth on any of their connected links.

[**0074**] In a preferred distributed implementation of SMDN **100**, portions of the information from TABLE **1** are distributed to nodes throughout the network. In one implementation, each node calculates the amount of reserved protection capacity on each of its incident links and broadcasts that information to the other nodes in the network. For example, node N**5** in SMDN **100** keeps track of the protection capacity reserved on links L**3**, L**4**, and L**6**. This corresponds to the information from TABLE **1** in the rows labeled with those link designations (i.e., L**3**, L**4**, and L**6**). Likewise, node N**4** keeps track of information relevant to links L**1** and L**3** (corresponding to the rows labeled L**1** and L**3** in TABLE **1**). Note that nodes N**4** and N**5** both keep track of information relevant to link L**3**. A secondary mechanism (e.g., periodic refresh or localized flooding) is used to keep the (now distributed) information of TABLE **1** current and up-to-date at the other nodes in the network. Each node can also keep track of the full network information (e.g., the complete information in TABLE **1**) for use in calculation of primary and restoration paths as needed to service new bandwidth requests.

[0075] Calculation and Distribution of Sharing Database

[0076] In steady-state operation of a shared mesh data network, it is assumed that once a new demand (i.e., service request) is received at a node, a route computation routine is invoked that calculates both a primary path (also known as "working path") as well as a protection path (also known as "restoration path") for the demand. Signaling (e.g., SNMP, PNNI, or RSVP-TE signaling) is used to establish the primary path for the service and to reserve bandwidth for the protection path. The signaling along the protection path carries the information of the primary path in terms of its demand bandwidth as well as nodes and links it contains. For each of the links incident to a node in the protection path, the node updates its local reserved bandwidth database (corresponding to its portion of TABLE **1**). This update involves incrementing, by the requested demand bandwidth, the value in each entry of each relevant row that corresponds to a link or node in the primary path (i.e., those links or nodes that, upon failure, would cause a disruption in a service along the primary path and thereby levy a bandwidth demand on the links in the corresponding protection path). The update also involves calculating the maximum value of each updated row. Note that a link connecting two nodes can be a downstream link for each node in different directions. It is assumed that for a particular protection path, the upstream node to the link computes and updates the sharing information (for an optical network, this may also include selection of the time slots, wavelength, and ports) and then passes this information to the downstream node so that both nodes connected to link have the same view of resources and sharing for the link. This scheme is specifically useful in cases where primary and protection paths are bi-directional.

[0077] As an example, consider the arrival of a request for shared mesh protection service between nodes **N4** and **N2** of SMDN **100**. Assume that, at the arrival of the request, the network was in a state captured by **FIG. 1** and TABLE **1** of **FIG. 2**. Further, assume that LSP-**11** (i.e., **N4**-L**3**-N**5**-L**4**-N**2**) and LSP-**12** (i.e., **N4**-L**1**-N**1**-L**2**-N**2**) are the primary and protection paths, respectively, determined to service this request. As before, signaling along the primary path is used to establish or provision the primary LSP. Also, as before, signaling along the protection path is used to carry the route information as well as the bandwidth demand (assumed in this example to be one unit) of this new service to all the nodes (i.e., **N4**, **N1**, and **N2**) in protection path LSP-**12** for the new primary path LSP-**11**. As a result, rows L**1** and L**2** of TABLE **1** will be updated (centrally or, in the case of a distributed architecture, at nodes **N4** (just row L**1**), **N1** (both rows L**1** and L**2**), and **N2** (just row L**2**)). The update result is captured in TABLE **2** of **FIG. 3**. Note that an additional one unit of bandwidth is now needed on both links L**1** and L**2** to guarantee the recovery of the new connection request (LSP-**11**) from a failure along its working route (i.e., **N4**-L**3**-N**5**-L**4**-N**2**).

[0078] Note that the availability of the complete sharing-information table (e.g., TABLE **1** or TABLE **2**) at each node allows for more efficient computation of primary and protection paths; however, this is not a requirement for achieving sharing. In the case of a centralized architecture, this capability comes for free, since the complete sharing-information table resides on a centralized server and may be made available to each node through a centralized command signaling structure (e.g., SNMP). In the case of a distributed architecture, similar capability can be achieved at the cost of periodically exchanging the information of the complete sharing-information table between nodes. Thus, a centralized approach provides savings in terms of this inter-nodal exchange of information, while a distributed approach provides additional robustness (e.g., the elimination of a single point of failure) and scalability.

[0079] Connection Routing and Service Set-Up Process

[0080] In one or more embodiments of the present invention, a failure along a primary path for a service is typically detected at the destination node of the service and signaled to the source node for the service. In response to this failure signal, the source node then switches traffic for the service over to a pre-established protection path that is disjoint from the primary path. The bandwidth to support the service is typically reserved (but not allocated) on the protection path at the time of the primary service setup. Note that the capacity on the restoration path, including the bandwidth reserved to support the primary path just discussed, is potentially shared among multiple other services that do not have common elements in their primary paths. Note that in case of shared restoration, the source first establishes a pre-computed restoration path and then switches the traffic to it. For achieving sharing in optical networks, one would use shared restoration as opposed to shared protection because an established optical path physically occupies resources such as time slots, wavelengths and thus does not allow their sharing until they are released by deleting the optical path.

[0081] In one embodiment of the present invention, a network manager is responsible for the determination of primary and restoration paths for services in the network such that sharing is increased and hence network cost (in terms of bandwidth or other cost elements) is decreased, network revenue is increased, and/or sufficient capacity is reserved on the restoration path to provide for reasonable robustness of the network to failures.

[0082] In a different embodiment, distributed calculation of primary and restoration paths is performed in the network elements, as opposed to centralized calculation, since it provides better scalability and reliability. Whenever a connection request arrives at a source node, a distributed element of the network manager has the task of calculating cost-efficient primary and restoration paths. To do this, the portion of the network manager associated with the source node needs information about the link states in the network. Nodes maintain local link-state information about the links incident to them. This information, along with sharing information (which can be classified as additional link-state information), is advertised, using a data network, to other nodes in the network. Hence, all nodes in the network, and ultimately the network manager (which may be a stand-alone, centralized entity, a distributed entity, or intrinsically a part of one or more of the nodes in a network), will eventually have the information on the state and sharing characteristics of all the links in the network that is needed to make the primary and restoration path calculations for this new connection. (Note that link-state information describing topology and bandwidth availability provides sufficient information to compute a legitimate pair of primary and restoration paths. The sharing information, however, additionally allows for the computation of a more efficient

primary/restoration path pair). Once the paths are calculated, service is setup on the primary path, and the required bandwidth for the service's restoration path is reserved on the restoration path.

[0083] The process of reserving bandwidth on the restoration path is similar to the process of connection setup on the primary path. In particular, a reservation message is sent to along the restoration path to each of the transit (i.e., intermediate) nodes along the path. This reservation message is analogous to the connection setup message that is sent along the primary path. One difference between the two messages is that the reservation message contains not only restoration path structure information, but additionally information about the primary path structure, while the connection setup message contains structure information about only the primary path. Using this additional information, transit nodes along the restoration path (or a regional manager that is responsible for one or more of these transit nodes) can assess whether sharing of link restoration bandwidth is possible.

[0084] In particular, each transit node (or its regional manager) executes a process similar to that illustrated by the flow diagram of **FIG. 4** for its incident links that are part of the restoration path. Note that each node along the restoration path (including the source node) verifies, for the link connected to it in the downstream direction, whether it is possible to use already allocated restoration capacity for protecting the primary path and, if not, it allocates any additional capacity that is required on the link as long as that capacity is available. It also updates the sharing information for the link accordingly. Therefore the processing in **FIG. 4** applies to all the transit nodes along the restoration path except for the destination node.

[0085] Namely, in step **400**, the node receives and parses the restoration message and determines the bandwidth requirements that would be levied on the link (that is connected to it in the downstream direction along the restoration route) if there were to be a failure in one of the links that make up the primary path. In step **402**, the node compares this bandwidth with the existing bandwidth requirements of primary links for which it is currently providing restoration bandwidth and determines if this new restoration path bandwidth can be shared with other restoration paths that are already reserved on the link.

[0086] If the bandwidth can be shared, then, in step **404**, the node accepts the restoration path for the link. Next, in step **406**, the node updates the sharing information associated with the link, and, exits the process in step **408**.

[0087] If the bandwidth for the new restoration path cannot be shared, then, in step **410**, the node determines whether the new restoration path bandwidth requirements can be supported by the existing capacity of the link. If it can, then, in step **412**, the node reserves the necessary additional bandwidth on the link and the process proceeds to step **404** as described previously. If, in step **410**, it is determined that the additional bandwidth required by the new restoration path would require an aggregate reservation of bandwidth on the link that exceeds the capacity of the link, then, in step **414**, the node rejects the restoration path for the link, and, in step **408**, the process exits.

[0088] Note that the above process can be performed in parallel on each of the transit nodes in the network.

[0089] For more optimal computation of primary and restoration paths in a distributed implementation, it is desirable (though not necessary) to distribute the changes in the links-state or sharing information to the other nodes in the network. However, disseminating this information for any possible change is quite expensive in terms of bandwidth and processing required. Therefore, typically, various methods are employed (e.g., based on thresholds) to limit the frequency of dissemination.

[0090] When sharing information is also being disseminated to other nodes along with the traditional link-state information, then, in addition to limiting the dissemination frequency, it is highly desirable to also address the size of the information itself. A reduction in the size of the sharing information can be achieved by using a scheme to represent the information in a compact form, by only disseminating the most critical information, or by using a combination of both.

[0091] Link-State Descriptions

[0092] In one distributed implementation of the present invention, where the computation of primary and restoration paths as well as initiation of their setup is distributed across the network, it is typical for only those nodes connected to a link to have complete visibility into the state of bandwidth allocations and bandwidth sharing on the link. Some of this information (e.g., available and currently allocated bandwidth on the link) should be distributed to other nodes in the network so they can compute primary and restoration paths. (Note that without this information the nodes may end up computing paths through congested segments of the network, thereby causing unnecessary crankbacks. This process can go in cycles and can significantly degrade network performance. Therefore, typically it is assumed that some minimal bandwidth information is disseminated to allow computation of a path through the network).

[0093] Link-state structure of traditional link-state protocols (OSPF, ISIS) has already been extended to include this necessary bandwidth information. The extensions are referred as the traffic engineering extensions (OSPF-TE, ISIS-TE).

[0094] In addition to bandwidth information, it is also desirable to exchange bandwidth-sharing information between nodes. Bandwidth sharing information allows computation of more optimal paths (e.g., that improve sharing) that can considerably reduce the required amount of restoration bandwidth, and thus the overall cost of the network. However, before employing any scheme (link-state routing, signaling, etc.) to distribute the sharing information, it is highly desirable to define compact representations of the data so dissemination of the data does not become a significant burden on the routing (OSPF-TE, ISIS-TE) and signaling (RSVP-TE, CR-LDP) protocols.

[0095] Conceptually, bandwidth-sharing information that gives the state of sharing at each link can thus be classified as link-state information. A number of different compact representations can be used to represent the sharing information in the link-state structure. These different compact representations may provide less than the full amount of information available regarding the sharing. However, beneficially, these representations take fewer bits to communicate the information used by the manager to update link-

state information globally and to calculate primary and restoration paths associated with new service requests. The link-state descriptions are best illustrated in the context of a link that is part of the restoration path of a number of primary paths, such as link L5 of **FIG. 5**.

[0096] **FIG. 5** illustrates exemplary network **500**, which includes sub-network **502**, sub-network cloud **504**, and exemplary restoration-path link L5. Sub-network **502** includes nodes NA, NB, NX, NY, and NZ and links L1, L2, L3, and L4. Link L5 is bounded by nodes NQ and NR and is connected to sub-network **502** via sub-network cloud **504**. The actual links connecting link L5 to sub-network **502** are not pertinent to this discussion and are thus not shown explicitly but instead are abstracted by cloud **504**.

[0097] In the present example, network **500** currently supports four different services on four primary paths. The first service is between nodes NX and NZ and is carried by a primary path along L1-L2-L4. The second service is between nodes NA and NY and is carried by a primary path along L2-L3. The third and forth services are between NB and NY and they are carried by two different primary paths along L3.

[0098] The four services are protected by restoration paths R1, R2, R3, and R4. Note that each of these restoration paths includes link L5. In the following sections, various representations of the sharing information will be described using L5 as an example.

[0099] Aggregate Node-Link Vector

[0100] A first representation of the sharing information for L5 is the aggregate node-link vector representation. This representation captures minimum sufficient sharing information that is required for a link to correctly compute the amount of restoration capacity required on it to provide guaranteed restoration to an additional primary path while realizing sharing, and to correctly deduce any required release of restoration capacity on deletion of a primary path. Note that this representation is very closely related to the row representation as illustrated in TABLE **1** and TABLE **2** of **FIGS. 2 and 3**, respectively.

[0101] In this representation, a vector is formed such that each element of the vector corresponds to a component in the network (e.g., a node or link) whose failure might contribute to the bandwidth reservation requirements of link L5. For the exemplary network of **FIG. 5** and the four exemplary primary path services, the elements include NA, NB, L1, L2, L3, and L4. (Note that, for the present example, nodes NX, NY, and NZ are not considered as elements of the aggregate node-link vector, because they are terminal nodes (i.e., source or destination nodes) and not intermediate nodes for the four services protected by link L5.) The value in each position of the vector represents the aggregate bandwidth that would be required on link L5 in the event of a single failure in the network of the network element that corresponds to that vector position. **FIG. 6** illustrates aggregate node-link vector V_{nia} for link L5 associated with the exemplary network **500** of **FIG. 5**.

[0102] For this example, it is assumed that the bandwidth demand of each service is of unit value, however, extension to the more general case of non-unit bandwidth demands would be understood to one skilled in the art. As illustrated, the value of the vector in the position corresponding to node NA is 1. This indicates that, for a failure of node NA, an aggregate bandwidth demand of 1 (associated with protection path R1) will be placed on link L5 corresponding to one (unit bandwidth) service. Similarly, the 2 in the position of V_{nia} corresponding to node NB indicates that for a failure of node NB, link L5 will be required to support two aggregate (unit bandwidth) services paths (i.e., associated with protection paths R1 and R2). Similarly, potential failures of links L1, L2, L3, and L4 correspond to aggregate bandwidth reservation values in V_{nia} a of 1, 2, 3, and 1, corresponding to restoration paths R1, R1+R2, R2+R3+R4, and R1, respectively. Note that the bandwidth that is reserved on link L5 is the maximum of the bandwidth requirements associated with any single network component failure. In the example network of **FIG. 5**, the reservation bandwidth is thus max $\{1, 2, 1, 2, 3, 1\}=3$.

[0103] As discussed earlier, to provide sharing, each node in the network keeps track of the aggregate node-link vector for all directly connected links. To share this information across the network (useful for computing more optimal primary and restoration paths), in one implementation, each node disseminates aggregate link-node vectors for its connected links. For a large network, this may turn out to be expensive because of the sheer size of each aggregate node-link vector. Other implementations involve sending a more compact representation of the sharing information. This compact representation, which summarizes the aggregate node-link vector information, is still useful in computing more efficient primary and restoration paths. Some of the compact representations are described in the following section.

[0104] Node-Aggregate Vector

[0105] An alternative representation of the link-state sharing information is referred to as a node-aggregate vector, designated V_{na}. **FIG. 6** also illustrates the node-aggregate vector V_{na} for link L5 of exemplary network **500** of **FIG. 5** as well as its derivation from the aggregate node-link vector V_{nia}. As illustrated, each element of V_{na} corresponds to a node in the network (although not all network nodes need to be included in V_{na}) and is a function of the node itself, specifically, the reservation values associated with all links incident to the node. The value 2 corresponding to node NA, for example, is derived from V_{nia} by taking the maximum of the reservation values for node NA and links L1 and L2, which, as can be seen from **FIG. 5**, are the links incident to node NA. Similarly, the value 3 corresponding to node NB is derived from V_{nia} by taking the maximum of the reservation values for node NB and its incident links L2, L3, and L4.

[0106] Binary Node-Link Vector

[0107] Another alternative representation of the link-state sharing information is referred to as a binary node-link vector, designated V_{nlb}. **FIG. 7** illustrates the binary node-link vector V_{nlb} for link L5 of the exemplary network of **FIG. 5**. The binary node-link vector V_{nlb} is created by a transformation of the aggregate node-link vector V_{nla} . Namely:

[0108] $V_{nlb}(j)=1$; if $V_{nla}(j)$=reservation bandwidth for the link

[0109] $V_{nlb}(j)=0$; otherwise.

[0110] In other words, the binary node-link vector V_{nlb} indicates which network element failure will cause activation of all the bandwidth that was reserved for restoration paths on the link. So, for example, as illustrated in **FIG. 7**, all elements of vector V_{nlb} are zero, except for the element corresponding to link **L3**, since only the failure of link **L3** will require all of the bandwidth (i.e., 3 units) reserved on link **L5**.

[0111] Node-Binary Vector

[0112] Yet another alternative representation of the link-state sharing information is referred to as a node-binary vector, designated V_{nb}. **FIG. 7** also illustrates the node-binary vector V_{nb} for link **L5** of the exemplary network of **FIG. 5** as well as one method for its derivation from the binary node-link vector V_{nlb}. As illustrated, each element of V_{nb} corresponds to anode in the network (although not all network nodes need to be included in V_{nb}) and is a function of the node itself, specifically, reservation values associated with all links incident to the node. The value 0 corresponding to node NA, for example, is derived from V_{nlb} by taking the maximum (or the binary OR) of the reservation values for node NA and its incident links **L1** and **L2**. Similarly, the value 1 corresponding to node NB can be derived from V_{nlb} by taking the maximum (or the binary OR) of the reservation values for node NB and its incident links **L2**, **L3**, and **L4**. Alternatively, the binary node vector V_{nb} can be derived from the node-aggregate vector V_{na} as follows:

[0113] $V_{nb}(j)=1$; if $V_{na}(j)$=reservation bandwidth for the link

[0114] $V_{nb}(j)=0$; otherwise. Note that V_{nb} can also be derived directly from V_{nla}.

[0115] Other alternative representations of the link-state sharing information, including inverted binary, real-number valued, and delta representations relative to other elements of the vector or a constant, as well as compressed (e.g., entropy, Huffman, or run-length encoded) versions can be used as would be understood to one skilled in the art.

[0116] Note that the previous descriptions of vector representations of sharing information assumed a homogeneous network where all service requests are of unit bandwidth. Extension of these concepts to cases involving non-unit, real-valued bandwidths of new and existing services would be understood to one skilled in the art.

[0117] Sharing Determination and Updating Sharing Information

[0118] To understand the operation and use of the sharing information vectors, consider the addition of a new service to exemplary network **500** of **FIG. 5** as illustrated in **FIG. 8**. A primary path node-link vector V_{pnl} for the new service **802** of **FIG. 8** is illustrated in **FIG. 9**. A vector element of a primary path node-link vector V_{pnl} is assigned the bandwidth of the service demand if the element position corresponds to a network component that is in the primary path and a value of zero otherwise. So, the primary path node-link vector V_{pnl} for new service **802** includes ones (because, in this example, we are assuming unit demands) in positions corresponding to node NB and links **L2** and **L4** and zeros in the other positions.

[0119] Assuming the restoration path for the new service path traverses link **L5**, it is of interest to determine whether this new restoration path can share the bandwidth of this target link **L5** with its presently supported restoration paths.

[0120] Aggregate Node-Link

[0121] One way to make this determination is to add the primary path node-link vector V_{pnl} associated with the new service path to the aggregate node-link vector V_{nla} that was associated with the previous aggregate reservation on target link **L5**. This addition is done on an element-by-element basis to form a sum vector V_{snl}. The maximum value of this resulting sum vector is then compared to the current reservation bandwidth of link **L5**. If the maximum value is equal to the current restoration bandwidth, then the restoration path for the new service can share the bandwidth reserved for the restoration paths of the existing services. Otherwise, supporting the new restoration path will require reservation of an additional bandwidth unit. In the case of the exemplary new service **802** of **FIG. 8**, the sum vector V_{snl} resulting from the vector addition of the primary path node-link vector V_{pnl} of **FIG. 9** and the aggregate node-link vector V_{nla} of **FIG. 6** is {1,3,1,3,3,1}, where the maximum value is three, which is equal to the current reservation bandwidth on link **L5**. Thus, the restoration path for this new primary path may be added to link **L5** without the reservation of additional bandwidth on link **L5**.

[0122] The determination of whether link **L5** can be shared corresponds to step **402** of the method of **FIG. 4**, which is performed by a node incident to link **L5** after receiving a restoration path request message. Continuing this example, following this determination of the ability to share in step **402**, the restoration path bandwidth is accepted (step **404**) and the sharing information associated with link **L5** is updated (step **406**). This updating is done by setting the updated aggregate node-link vector V_{nla}^{u} equal to the sum vector V_{snl} or, in other words $V_{nla}^{u}=V_{nla}+V_{pnl}$. A subsequent determination of sharing ability for link **L5** would then be performed using V_{nla}^{u}.

[0123] To calculate, in an optimal way, the primary and restoration paths at the source node, one could advertise sharing information in the network using the aggregate node-link vector form or one of its compact representations so that each node would have information about which links can share the restoration bandwidth. Note the compact representations only provide a summary of the sharing information.

[0124] Computation of Routes Based on Multiple Cost Criteria

[0125] The link state information (bandwidth allocation) and sharing information as outlined previously can be used to compute cost-efficient connection routes within a network. For path computation, link state can be reduced to an equivalent link cost and then route-computation algorithms can be considered that minimize the total path cost —where the path cost is considered to be the sum of the link costs. The link-cost function should be carefully designed. Also, depending on the possibility of sharing bandwidth on the restoration path, link costs will be different for the sharing case compared to the no-sharing case. (Note in case of sharing case, sharing information can be used to compute more cost-efficient paths through the network. This can be achieved by incorporating sharing information in the link-cost metric). The two cases are described below.

[0126] No-Sharing Case

[0127] Link-cost calculation is based on the administrative weight (AW) of the link, the link capacity (LC), and link's available capacity (AC). Under light and medium link utilization (LU), where LU is less than a specified utilization threshold (UT) (i.e., LU<UT), link cost when sharing is not considered W^{NS} is set equal to the AW, i.e., W^{NS}=AW. Hence, under light load conditions, the link-calculation algorithm will assign links to services according to the preferences (i.e., administrative weights) assigned by the network operator. When the link load is high (LU>UT), however, the link weights are preferably calculated with the objective of load balancing and revenue maximization. The generic formula for the link cost w^{NS} in this high link utilization region is based on the inverse of available capacity:

$$w^{NS} = \frac{AW \cdot MWC}{AC^f} \tag{1}$$

[0128] where MWC is maximum weight coefficient (i.e., an additional scaling factor introduced to provide continuity between the two regions of light and heavy loads) and f is an exponentiation factor (nominally set to 0.4) used to modify the available capacity variable AC. Motivation, a detailed model, and additional numerical support for this approach of weight calculation based on the inverse of available capacity are described in Dziong, Z., "ATM Network Resource Management," McGraw-Hill, 1997, (herein "Dziong '97") incorporated herein by reference in its entirety.

[0129] Sharing Case

[0130] When sharing information is available, it can be used to compute more cost-efficient (more optimal) primary and restoration paths. For example, an algorithm can be designed to compute, for each possible primary path, the lowest-cost restoration path by utilizing the sharing information. Then, from the set of all primary and restoration paths, the pair that requires the least amount of additional capacity can be chosen. This path computation algorithm using the sharing information can give considerably better paths than an algorithm using no sharing information.

[0131] Sharing information can be used in finding the least-cost restoration path for a given primary path. It involves adjustment of the link cost (lowering of it) based on the amount of sharing that is possible on a link along the restoration path of a particular primary path. This can be achieved by computing the sharing degree of each link in the network given the primary path. (Note that only links that are disjoint to the primary path need to be considered).

[0132] The sharing degree is defined as the maximum number of additional (unit bandwidth) primary services (along the proposed primary path) that can be added to the link without increasing the restoration bandwidth requirement of the link. In a sense, this metric provides a network planner with an idea of the restoration headroom on a link with respect to the proposed primary path. The higher the sharing degree, intuitively, the better the choice of the primary path for the new service, since a larger sharing degree for a primary path would allow future demands to be added along that path without the need to reserve additional restoration bandwidth.

[0133] Sharing degree can be calculated from the aggregate node-link vector V_{nla} representation of sharing information and the primary path node-link vector VP representation according to the following relationship:

$$SD = \text{the maximum value m for which max } \{m \cdot V_{pnl} + V_{nla}\} = RB,$$

[0134] where RB is the current reservation bandwidth on the link under consideration.

[0135] A less accurate measure of sharing degree can be calculated using the compact representations of the aggregate node-link vector. Note that less accurate means that the sharing degree provides a conservative indication of which links may be better, but does not provide the exact bandwidth available for sharing for a particular primary path.

[0136] Sharing degree can be calculated from the node-aggregate vector V_{na} representation of sharing information and the primary path node vector VP_{pn} representation according to the following relationship:

$$SD = \text{the maximum value m for which max } \{m \cdot V_{pn} + V_{na}\} = RB.$$

[0137] Sharing degree can also be calculated using the binary representation of node-link or node vector. In case availability of sharing information in terms of the binary node-link vector V_{nlb} for a link, the sharing degree can be computed by first deriving a binary primary path node-link vector V_{pnlb} from the primary path node-link vector V_{pnl} (in the similar fashion that V_{nlb} can be derived from V_{nla}), then taking an AND of the V_{pnlb} (binary primary path node-link vector) and V_{nlb} (binary node link vector representation of the sharing information on the link), and then taking the bit OR of the resulting vector. If the result is one, sharing is not possible and sharing degree is zero. If the result is zero, then sharing is possible and sharing degree is one Note that the sharing degree obtained in this manner using the binary node-link vector does not give the exact amount of sharing that is possible on the link for the primary path. It only indicates whether sharing is possible or not.

[0138] Similarly, a more crude sharing degree can be derived by using the binary node vector information.

[0139] When bandwidth sharing is possible for a link, it would appear that there is no immediate bandwidth-related cost for new restoration path reservation using that link. However, when applying the Markov decision theory framework described in Dziong '97, there is a cost. This follows from the fact that the cost should be considered during the whole connection-holding time, not just at the instant of a new connection arrival. The Markov process makes it possible to consider the probabilistic cost of using the link, since, even if sharing is possible at the moment of connection arrival, in the future, with some probability, the other shared connections can be terminated and the new connection will be the sole occupant of the reserved bandwidth on that link, and hence incur a cost for reserving additional restoration bandwidth in the network. While exact calculation of such a cost seems to be very difficult, if possible, one can use this argument to employ a non-zero link cost even

when sharing is possible. In one implementation, this fact can be accommodated by calculating link cost according to the following equation:

$$w^S = \frac{w^{NS}}{(1 + b \cdot SD)} \tag{2}$$

[0140] where w^s is the link cost considering sharing degree, w^{NS} is the link cost without considering sharing degree, and b is a specified coefficient.

[0141] **FIG. 10** depicts an exemplary procedure for calculating a path's cost as a function of link utilization and sharing (assuming the path is a restoration path) as per the above discussion. As illustrated, in step **1000**, the procedure inputs Path (e.g., the link IDs for a path), Option (Option=1 if the path cost is to be calculated without consideration of whether sharing is available or not, and Option=2 if sharing is to be considered), and additionally a primary path if Option=2 (since sharing is a function of a path relative to the primary path that it protects). Next, in step **1002** the first link in Path is selected for cost assessment. The variable PathCost is initialized to zero in step **1004**, and in step **1006**, a test is performed to determine if the link utilization is below a specified utilization threshold. The utilization threshold (UT) for the system is determined by analysis and nominally set to 80%. If the utilization is below or equal to the threshold, then in step **1008**, the link cost is set to AW. If the link utilization is above the threshold, then in step **1010** the link cost is set according to equation 1. In either case, in the test of step **1012**, the variable Option is checked to see if it is set to the no sharing option. If it is, in step **1014**, the PathCost is incremented by the link cost. If Option!=1 (e.g., the "consider sharing" option), then in step **1016***a* test is performed to see if sharing is available on this link. If it is, then in step 1018, the link cost is assigned a value according to equation (2) (where it is a function of the link cost calculated for the no-sharing option and the sharing degree calculated using the primary path that was passed to the procedure) and in either case (whether sharing is available or not on the link) in step **1014**, PathCost is incremented by the new link cost. Next, in step **1020**, a test is performed to determine whether all the links in Path have been processed. If they have, in step **1022**, PathCost is returned to the calling procedure, if not, in step **1024**, the next link is selected from Path and step **1006** the processing continues with the link utilization test as described previously. The path cost procedure of **FIG. 10** can thus be seen to calculate a path cost of a primary path or a restoration path (if a reference primary path is provided in the latter case). It can also be used to calculate a path cost with consideration of sharability of links in a path (Option=2—only applicable to restoration paths with respect to a given primary path) or without consideration of the sharability of a link.

[0142] **FIG. 11** depicts and exemplary method for calculating a minimum-cost primary/restoration path pair for a new service in consideration of link utilization, utilization threshold, administrative weight, and sharing degree. As will be seen, **FIG. 11** can make use of the procedure illustrated by **FIG. 10** to calculate the path cost in certain steps. As depicted, in step **1100**, the bandwidth and source and destination IDs for a new service are input. The method involves two major flows. In the first flow, illustrated by steps **1102**, **1104**, **1106**, and **1106**, one minimum-cost path pair is selected from K candidate pairs by a first method. In the second flow, illustrated by **1110**, **1112**, **1114**, and **1116**, one minimum-cost path pair is selected from L candidate pairs by a second method. Then in step **1118**, and steps **1120** or **1122**, the lowest-cost pair of these two lowest-cost results is selected as the overall minimum-cost pair.

[0143] Specifically, in step **1102**, the first flow starts with selection of K minimum cost primary paths with the assistance of the Path Cost routine of **FIG. 10** using Option=1 (i.e., no sharing considered). Next in step **1104**, a set of K minimum-cost restoration paths are calculated and priced using the assistance of the PathCost routine of **FIG. 10** using Option=2 (e.g., where sharing is considered and the appropriate primary path is passed to the PathCost routine). Then, in step **1106**, the Path Costs that were calculated in steps **1102** and step **1106** are used in the calculation of a sum of the pair cost for each of the K primary/restoration path pairs. In step **1108**, the minimum sum is saved in the variable LowKSum and the minimum-cost pair is saved in the data structure LowKPair.

[0144] In step **1110**, the second flow starts with the calculation of L disjoint lowest total-cost pairs of paths for the new service where cost is determined for each path using the PathCost routine of **FIG. 10** with Option=1 (e.g., no sharing considered). Next, in step **1112**, the cost of each of the L restoration paths that were determined in step **1110** is recalculated using the PathCost routine, this time with Option=2 (e.g., sharing considered) and the appropriate primary path passed to the routine. Next in step **1114**, the sum is calculated of the cost of the primary and the restoration path for each of the L pairs and in step **1116**, the lowest sum is stored in the variable LowLSum and the lowest-cost pair is stored in the data structure LowLPair.

[0145] Finally, in the test of step **1118**, LowKSum is compared to LowLSum. If LowKSum is lower than or equal to LowLSum, then in step **1122**, LowKPair is selected as the minimum-cost path pair. If it is not lower, then in step **1118**, LowLPair is selected.

[0146] Disjoint Path Calculations

[0147] When sharing is not permitted (e.g., when a 1+1 restoration scheme is the best option available for restoration) or not considered until after calculation of the restoration path, the link costs for primary and restoration paths are considered to be the same, and both paths can be calculated using a minimum-cost node-link disjoint optimal algorithm. This algorithm for N disjoint shortest-path calculations is a special case of the "successive shortest-path algorithm," independently developed by Jewell, Iri, and Busaker and Gowen. More information on the successive shortest-path algorithm can be found in W. S. Jewell, "Optimal flow through networks," Technical Report 8, Operations Research center, MIT, 1958; M. Iri, "A new method of solving transportation-network problem," Journal of the Operations Research Society of Japan, 3:27-87, 1960; and R. G. Busaker and P. J. Gowen, "A procedure for determining a family of minimum cost network flow-patterns, Technical Report 15," Operations Research Office, Johns Hopkins University, 1961, each incorporated herein by reference. This algorithm can be implemented in several different ways with varying complexity. One of the well-

known implementations was derived by Suurballe in J. W. Suurballe, "Disjoint paths in a network," Networks, pp. 125-145, 1974, incorporated by reference herein in its entirety. A slightly different version of this algorithm is well described in J. W. Suurballe and R. E. Tarjan, "A Quick Method for Finding Shortest Pairs of Disjoint Paths," Networks, Vol.14 (1984) 325-336, incorporated by reference herein in its entirety, for two disjoint shortest-path calculations.

[0148] When sharing is taken into account during the path calculation, the link costs for restoration paths are a function of the primary path (via the sharing degree) as indicated by Equation (2). The situation is similar when taking into account shared risk link groups (SRLGs). An SRLG is a set of two or more links, for which a failure of any one link in the SRLG is associated with a relatively high risk of failure of the other links in the SRLG (e.g., having a risk of failure of the other links in the SRLG greater than a specified risk threshold). For example, when different links correspond to different optical fibers and two or more optical fibers are physically bundled together, there is a shared risk that all of those links will fail together, e.g., as a result of a cut in the bundle. Such a set of links may be said to form a shared risk link group. When considering SRLGs, each link that is part of the same SRLG as a link in the primary path is assigned a cost that is a function of its membership in that group.

[0149] In general, in calculation of minimum cost primary/restoration paths for both SRLG and non-SRLG cases, the optimal solution is not feasible in a reasonable time. Therefore, an efficient heuristic may be used that includes the following steps:

[0150] 1) Create an "intelligent" sequence of potential primary paths for a new service (K minimum cost paths and L disjoint path pairs).

[0151] 2) For each primary path, calculate a node-link disjoint (or SRLG-disjoint as specified) shortest restoration path.

[0152] 3) Select the minimum-cost pair of disjoint paths.

[0153] Consideration of Shared Risk Link Groups

[0154] Consider a communications network consisting of nodes and links interconnecting those nodes. Each link is at a minimum characterized by its bandwidth expressed in bandwidth units. In general, each connection or service in the network is carried by a primary path that (1) connects the source and destination nodes and (2) provides the necessary bandwidth for the service.

[0155] Primary/Restoration Paths: Disjoint for Protection

[0156] Some of the services can be protected against a single transit node or link failure. This protection is made possible by selecting a protection or restoration path for the service that is node and link disjoint from the primary path except for the source and destination nodes. Whenever one of the primary path elements fails, the connection is switched automatically to the restoration path.

[0157] Primary Paths: Disjoint for Sharing

[0158] With the assumption that a restoration path is selected to be disjoint from its primary path, it can be seen that the bandwidth of a link that is part of multiple restoration paths can be shared if the primary paths (that are protected by the multiple restoration paths) are node and link disjoint from each other. This is because, when the primary paths are disjoint, a single network element failure is unlikely to impact two different primary paths. Thus, in the event of a failure, only one restoration path (from the considered set that shares bandwidth on the link) will be activated and only the bandwidth associated with that restoration path will be allocated.

[0159] Primary/Restoration Paths: SRLG-Disjoint for Protection

[0160] If shared risk link groups (SRLGs) are considered, where there is an increased risk of multiple failures within each SRLG (e.g., disjoint links that are bundled within the same share a common, a further restriction can be considered. In determining a restoration path for a primary path, no element (e.g., node or link) of the primary path should be from the same SRLG as an element of the restoration path, since, if it were, a failure of an element of the primary path might be coincident with a failure of an element of the restoration path and recovery would be hampered. Herein, paths that meet this broader type of disjointedness will be referred to as SRLG-disjoint.

[0161] Primary Paths: SRLG-Disjoint for Sharing

[0162] Similarly, with the assumption that a restoration path is always selected to be SRLG-disjoint from its primary path, it can be seen that the bandwidth of a link that is part of multiple restoration paths can be shared if the primary paths (that are protected by the multiple restoration paths) are SRLG-disjoint from each other. This is because, when the primary paths are SRLG-disjoint, a single network element failure is unlikely to impact more than one of them. Thus, in the event of a single failure, only one restoration path (from the considered set that shares bandwidth on the link) will be activated and only the bandwidth associated with that restoration path will be allocated.

[0163] Method of Calculation of Primary and Restoration Paths

[0164] **FIG. 12** illustrates one exemplary method for calculating primary and restoration paths that takes into account bandwidth sharing for restoration paths and considers the impact of shared risk link groups (SRLGs). Note that this procedure may also be used for calculation of primary and restoration paths when no SRLGs are considered by considering that each link as an independent SRLG.

[0165] As shown, in step **1200**, the source and destination nodes for a new service are input. Next, in step **1202**, a set of K shortest-path candidate primary paths are calculated (this can be done, for example using the PathCost routine of **FIG. 10** with Option=1). In step **1204**, the first of the K primary paths is selected for further processing. In step **1206**, a minimum-cost restoration path is calculated for this primary path. This calculation could be performed using the routine of **FIG. 10** (relevant for the non-SRLG case), but alternatively, in this embodiment of the present invention, the procedure illustrated by **FIG. 13** is preferably used, since it specifically addresses link cost as a function of SRLGs. The procedure of **FIG. 13** is discussed in more detail below. In step **1208**, the sum of the primary path cost (calculated in step **1202**) and the minimum-cost restoration path cost (determined in step **1206**) is stored along with identification

of the minimum-cost pair. In step **1210**, a test is performed to see if all of the K primary paths were considered. If not, in step **1212**, the next primary path from the group of K is selected and processing returns to step **1206**. If, in the test of step **1210**, it is determined that all the primary paths have been processed, then, in step **1214**, all the primary/restoration path pairs that were saved in step **1208** are analyzed to find the pair with the minimum total cost of primary and restoration paths. The procedure exits at step **1216**.

[**0166**] While one or more innovations of the present invention are used to assign a cost to a path, one approach to calculating the candidate paths themselves that are assigned costs per step **1202** of **FIG. 12** is described in Brander, A. W., Sinclair, M. C., "A Comparative Study of k-Shortest Path Algorithms," Proceedings of the 11th **1216** Performance Engineering Workshop, Liverpool, September 1995, pp.370, which is incorporated herein by reference in its entirety.

[**0167**] Calculating the Minimum-Cost Restoration Path for a Primary Path

[**0168**] As noted earlier, step **1206** of **FIG. 12** calculates a minimum-cost restoration path for a given primary path. An exemplary procedure for implementing step **1206** of **FIG. 12** is illustrated by **FIG. 13**. As shown, in step **1300**, the first link of the candidate primary path is selected and, in step **1302**, the shared risk link group(s) to which this link belongs are identified. Next, in step **1304**, the links in those SRLGs are excluded from further consideration by either eliminating them from the network graph or, equivalently, assigning an infinite cost to them. In step **1306**, a test is performed to determine whether all the links in the primary path have been considered. If not, in step **1308**, the next link from the primary path is selected and the procedure continues in step **1302** with the identification of the SRLGs to which the new link belongs.

[**0169**] If the test of step **1306** is true, and all the links for the current primary path have already been considered in step **1304**, then, in step **1310**, the first link of the remaining links in the network is selected for further processing. In step **1312**, a test is performed to determine whether the link's bandwidth can be shared with a restoration path for the selected primary path. Note that step **1304** guarantees that the links considered in step **1312** are already SRLG disjoint from the primary path. So, as discussed previously, the sharing determination includes determining whether the link is already being shared, to what extent, and by what restoration paths. Note that this determination is assisted by the sharing information that is disseminated to the nodes. If sharing is not possible, then, in step **1314**, a test is performed to see if all the remaining links have been considered for sharing. If not, then, in step **1316**, the next link of the remaining links is selected and the procedure continues with the test of step **1312**.

[**0170**] If the test of step **1312** determines that sharing is possible, then, in step **1318**, the cost of the sharable link is reduced by multiplying the link's current cost by factor R (nominally 1/100) and the procedure continues with the test of **1314**, where the determination is again made as to whether all the links from the "remaining links" set have been processed. If they have, then, in step **1320**, a minimum-cost restoration path for the primary path is calculated using the new link costs. The procedure exits at step **1322**.

[**0171**] Note that, here, bandwidth cost is typically being considered; however, in the more general case, other costs (e.g., administrative weight and link utilization) can be considered independently or via a multiple criteria function.

[**0172**] In general, path selection is a powerful tool that can be used to achieve several objectives such as network operator policies (e.g., preferences for certain links and/or priorities for certain demands), maximization of network resource utilization, and optimization of different restoration strategies. Each of these objectives is based on different input parameters and optimization models. For example, operator policy can be implemented by means of demand-dependent link administrative weights and shortest-path algorithms that minimize the administrative weight of the path. Maximization of network utilization can be achieved by using current link bandwidth utilizations in a path selection algorithm to achieve load balancing in the network. Different restoration strategies can be achieved by modifying network topology and link-cost functions in the process of path selection in order to achieve optimal restoration paths that can minimize restoration time and take into account SRLGs. One or more of these objectives can be combined into a unified framework. The framework can be decomposed into three main parts, each of which is concerned with the calculation of primary and shared restoration paths:

[**0173**] (1) Choice of the link-state description.

[**0174**] (2) Choice of the link-cost function used for calculation of primary and restoration paths.

[**0175**] (3) Choice of the algorithm for disjoint paths calculation.

[**0176**] For the purpose of primary path calculation, the advertised link-state description typically will contain administrative weight AW, available capacity AC, and total link capacity LC. This information supports calculation of the state-dependent link-cost function, which is then used to calculate minimum-cost primary paths. For the purpose of sharing link bandwidth by restoration paths, the node controlling the link is provided with an accurate but optimized representation of the sharing information.

[**0177**] Connection Set-Up Protocol Extension

[**0178**] Historically, protection bandwidth for networks was allocated at the time of the primary service setup. An example of this is the popular 1+1 protection scheme, wherein the bandwidth allocated along the protection path for a service was the same as the bandwidth allocated along the primary path for a service. In this case, the connection setup protocol was substantially identical at nodes along the primary and restoration paths, as was the information that was needed at those nodes. In particular, in order to set up a service connection between incoming and outgoing links of a transit node in the prior art, the identity of the incoming service, identity of the outgoing link, and the connection bandwidth required by the service were provided. Additionally, procedurally, this same information was provided to nodes along the primary and protection paths, and the protection bandwidth was allocated on the protection path at the time of establishment of the service on the primary path.

[**0179**] In one or more embodiments of the present invention, however, where sharing of link bandwidth is consid-

ered, additional sharing information is provided to transit nodes along the protection path during a pre-setup of the network. This sharing information is used by the transit nodes along the protection path to determine the amount of bandwidth to be reserved along the outgoing protection links of the transit node to support protection of a new service taking into consideration link sharing. Specifically, in the connection setup protocol, the identity of the incoming service, identity of the outgoing link, connection bandwidth required by the service, and primary path link information are provided to transit nodes along the protection path, while transit nodes along the primary path still receive the same information as in the prior art. In one or more embodiments of the present invention, the primary path link information can be provided using the primary path node-link vector V_{pnl} representation, or, less optimally, the primary path node vector V_{pn} representation, as described previously.

[0180] In addition, in embodiments of the present invention, bandwidth is not allocated on the links of the protection path, but instead is just reserved on the links and allocated only in the event of a failure along one or more of the primary paths that are protected by the links. For this reason, the protection path is often referred to as a restoration path.

[0181] The primary path information, together with the bandwidth requirement of the new service, provide sufficient information for the transit node to calculate whether bandwidth sharing is possible and what the total bandwidth requirement is for bandwidth reservation on the link.

[0182] The extension to the service setup procedure that supports sharing in mesh networks is illustrated by the exemplary procedure of **FIG. 14**. As shown, in step **1400**, a new service request is received. This may be at the source node for the service or more generally at a distributed or centralized service or network manager. Next, in step **1402**, a determination of a suitable primary/restoration path pair is made for the service. Then, in step **1404**, signaling is performed along the primary path for the service, wherein the identity of the incoming service, the identity of the outgoing link, and the bandwidth requirement of the service are provided to transit nodes on the primary path. Finally, in step **1406**, signaling is performed along the restoration path to achieve reservation of bandwidth for the service, wherein the identity of the incoming service, the identity of the outgoing link, the bandwidth requirement of the service, and the primary path link information (e.g., V_{pnl}) are provided to transit nodes on the restoration path.

[0183] Signaling along the primary and restoration paths can be implemented using suitable signaling protocols including one or more of a Craft interface, simple network management protocol (SNMP), transmission control protocol/Internet protocol (TCP/IP) direct connections, PNNI, RSVP-TE, and constrained route-label directed path (CR-LDP) protocol.

[0184] OSPF Exemplary Implementation

[0185] The principles described in this specification can be applied to a broad class of different networks by working within defined protocols for those networks and/or providing extensions to existing protocols for those networks. For example, sharing may be realized within Internet protocol (IP) networks by appropriate extensions to the protocols used within IP networks for distribution of link-state information and setup/reservation of paths.

[0186] As a specific example, a popular dynamic routing protocol used in autonomous systems built from IP networks is open shortest path first (OSPF). OSPF includes mechanisms for determination and distribution of link-state information. The distribution includes both time-based and trigger-based flooding mechanisms that support both full and incremental distribution of link-state information between nodes in the network. More information on OSPF can be found in Moy, J., "OSPF version 2, " RFC1247, July 1991, incorporated herein by reference in its entirety.

[0187] Recent extensions to OSPF include the opaque link state advertisement (LSA) option. This option effectively provides for the use of the OSPF flooding mechanism to distribute optional application-specific information in the OSPF IP messages that are flooded through a network. By defining an application-specific type for sharing information, the opaque LSA option allows sharing information, preferably in a compact and efficient format (e.g., node-link vector or node vector) to be distributed throughout the network and reach the various nodes that control the reservation and allocation of bandwidth on protection links within the network. The OSPF LSA option is described in Coltun, R., RFC2370-OSPF Opaque LSA Option, Network Working Group, July 1998, incorporated herein by reference in its entirety.

[0188] The sharing information that has been distributed to the nodes in the network can be used to calculate, reserve, and allocate bandwidth on links. Popular protocols used in IP networks for establishment of paths (also known as "tunnels" in the language of the RFCs that describe those protocols) are RSVP and RSVP-TE. RSVP and RSVP-TE are described in detail in R. Braden, Ed., et al., "Resource Reservation Protocol (RSVP)—version 1 functional specification," RFC2205, September 1997, and "D. Awduche, et al., "RSVP-TE: Extensions to RSVP for LSP tunnels", RFC3029, December 2001, respectively, each incorporated herein by reference in its entirety.

[0189] Shared Restoration Extensions to OSPF

[0190] The following describes how the concepts of shared restoration maybe applied to IP networks by appropriate extension of the OSPF/OSPF-TE protocols. These extensions allow OSPF/OSPF-TE to disseminate sharing information to nodes in an IP network and enable nodes to identify, for each new service, an optimal combination of a primary path and a restoration path, from source to destination, such that the amount of bandwidth reserved on the restoration path is minimized.

[0191] The extensions described herein assume an IP network with traffic engineering (TE) support such as that described by the multiprotocol label switched (MPLS) umbrella of protocols. More background information on MPLS-based recovery can be found in Sharma, V., Hellstrand, F., et al., "Framework for MPLS-based Recovery," IETF draft-ietf-mpls-recovery-frmwrk-07.txt, Sept. 2002 incorporated herein by reference in its entirety. More background on shared mesh protection under MPLS can be found in Qureshi, M., et al., "MPLS-TE Shared Mesh Protection," IETF draft-qureshi-mpls-shared-protection-00.txt, Oct. 2002.

[0192] The extensions described herein address the issues of supporting shared mesh protection in mesh networks that

is guaranteed for one failure at a time. It is assumed that the restoration path is disjoint from the primary path and is pre-computed and reserved at the time of the primary path setup. Bandwidth is reserved but not allocated prior to an actual failure. Once the failure of a primary path is identified, the protection path is then activated by allocating the reserved bandwidth, thereby supporting fast restoration. By reserving the bandwidth in anticipation of a failure but not allocating the bandwidth until the failure actually occurs, it is possible to share the reserved restoration bandwidth on a particular link among multiple other connections that do not have common elements (links, nodes) in their primary paths (other than the common source and destination nodes).

[0193] The pre-computation of the protection path can be done in one of several ways, depending on the available information. One way is to calculate a disjoint path using the same link weights as those used in the calculation of the primary path. In this case, one can use RSVP-TE extensions for shared mesh protection to compute locally, at every node along the protection path, the amount of shared protection bandwidth required on each of the links that constitute the restoration path. More information on this approach can be found in Liuh, H. A., et al., "RSVP-TE Extension for Shared Mesh Protection," IETF draft-liu-rsvp-mpls-shared-protection-00.txt, Oct. 2002 ("Liuh '02"), incorporated herein by reference in its entirety. While some sharing of protection bandwidth maybe realized in this approach, the amount of bandwidth reserved for recovery is typically not minimized since the sharing potential on each of the links is not known before the protection path choice is made at the source node.

[0194] In contrast, the proposed extensions to OSPF-TE provide for sufficient information to be disseminated to each node to support efficient restoration path calculation and a significant improvement in network utilization.

[0195] Given a primary path between a source-destination pair, there are a couple of different methods to compute the optimal restoration path. One way is to compute 'N' disjoint paths (with respect to the given primary) and then start a resource signaling procedure (through protocols like RSVP) to determine the path that would result in the least amount of bandwidth being reserved on each hop (link) of the protection path. Extensions to RSVP-TE have been proposed to allow for this computation; however, those extensions involve sending signaling messages across each of the nodes that constitute a potential restoration path, with likely crank-backs. In contrast, the proposed extensions to OSPF-TE make it possible to compute a primary and restoration path combination that utilizes the network resources efficiently with reduced signaling and a reduced crank-back load. These extensions to OSPF-TE are meant to work alongside the RSVP-TE extensions [Liuh '02] While the latter provides the minimal topological information needed for guaranteed restoration, the former allows for efficient use of network resources.

[0196] The information made available to network nodes by these extensions can be used to build an extended link-state database just as node link-state advertisements are used to build a "regular" link-state database. The difference is that the extended link-state database (referred to below as the TE/Share database) has additional link attributes. Uses of the TE/Share database include (1) monitoring the extended link attributes and (2) globally optimized computation of protection paths.

[0197] In this scheme, in order to support sharing/restoration, every node maintains a local sharing information database (e.g., the TE/Share database). This database contains a data structure for each link L that the node owns. The data structure for each link contains information (e.g., bandwidth, link-id) about all the other links in the network for which link L provides restoration capacity. Since this could be a large amount of information for a large network, only changes in this database are advertised. Note that, in practice, links are unidirectional. By convention, the node that owns a link is the one that is connected to the outgoing interface side of the link, and that node is the one that makes advertisements about the link.

[0198] As an example, let link L be an outgoing link from node R, where link L is part of a restoration path for a primary path of bandwidth B1, which passes through links L1, L2, and L3. Assuming that link L is not a part of any other restoration path, then the advertisements for link L from node R would be B1::L1,L2,L3. This advertisement says the bandwidth reserved on link L with respect to a failure of link L1, L2, or L3 is B1. If link L is subsequently used to provide restoration for another primary path of bandwidth B2, which passes through links L2, L4, L5, then the advertisements for link L from node R would then be B1+B2::L2; B2::L4,L5. Note that the new advertisement contains no information for links L1 and L3, since the protection bandwidth reserved on link L with respect to those links did not change. Note that B1+B2 bandwidth is now required to protect against the failure of link L2, since two primary paths share link L2, one of bandwidth Bi and one of bandwidth B2.

[0199] Each time a link is used as a restoration link, and the required shared-mesh-protection bandwidth is reserved, the TE/Share database is updated to reflect the changes if any that are necessary. Note that, although it is preferable for the TE/Share database to be different from the LSA database, it is possible to use a common database. However, since it is desirable to keep the LSA advertisements as small as possible, only the changes to the TE/Share database are advertised. Such a restriction might require a separation of the databases on most OSPF implementations.

[0200] Although the extensions proposed herein do not specify how to compute primary or restoration paths, they do provide information useful in making an optimal restoration path choice (with respect to a given primary path) from a network utilization standpoint.

[0201] In one implementation, the primary path is provided as a list of node-ids (i.e., the path is specified by the nodes through which it passes) by a route-database. However, to find out if indeed a primary path can be supported through the specified node-ids, and to determine the exact links through which it traverses, a signaling protocol such as the proposed extension to RSVP-TE [liuh '02] could be used.

[0202] Sharing

[0203] When a new service is added to a network, the source node or a network management entity has the task of determining appropriate primary and restoration paths for that service. Assuming a set of candidate primary paths can be calculated for the service as well as a set of potential restoration paths for one or more of those primary paths, it

is then of interest to determine, for each candidate primary path, a restoration path that offers the best sharing opportunity. One metric that can be used to evaluate a restoration path is the overall amount of additional bandwidth that must be reserved in the network to support protection of the new service using that restoration path. By choosing a restoration path that would require the minimum amount of additional bandwidth to be reserved along its links, an operator can reduce the overall impact to the available capacity in the network.

[0204] Assume that a candidate primary path P of bandwidth B_p is chosen for a new service. Assume further that a number of candidate restoration paths $R_1, R_2, R_3 \ldots, R_N$ are also chosen that are disjoint from primary path P. Let P-set be the set of all links that constitute primary path P. Let Rj-set denote the set of links Li ($i=\{1, \ldots, m\}$ where m is the number of links in Rj) that make up restoration path Rj. Next, let B-Li-set denote the set of links in the network for which link Li already provides restoration capacity (where for B was chosen here as a mnemonic for "backup"). With these assumptions, the following observations can be made:

[0205] (a) No sharing possible: If any B-Li-Set is null, then the corresponding link Li is not already providing restoration capacity for any link in the network. Since it is not already backing up any links, it does not currently have any reserved restoration bandwidth to share; and, if it were to be used as part of a restoration path for primary path P, then it would be necessary to reserve the full amount of the primary path's bandwidth B_p on link Li. In this case, the "cost" assigned to this link of the restoration path under consideration would be Bp. On the other hand, if B-Li-set is not null, then some sharing potential exists on link Li, but it still needs to be seen whether this sharing potential applies to any of the links of the primary path under consideration.

[0206] (b) Sharing possible—scenario A: For non-null B-Li-sets, it is of interest to see if any of the links that are protected by Li are in the primary path. If the intersection, denoted I-Li-set, between P-Set and the B-Li-Set for a link Li is null, then link Li is not providing protection for any of the primary path links, but it is providing some level of protection for links in other primary paths in the network that are disjoint from the primary path of interest. Thus, by definition, some protection bandwidth sharing is possible on link Li. There are two cases.

[0207] In the first case, the bandwidth Br(i) that is presently reserved on link Li is greater than or equal to Bp. In this case, no additional bandwidth need be reserved to protect the new service, and the cost of using this link of the candidate restoration path is zero.

[0208] In the second case, Bp is greater than the presently reserved bandwidth Br(i) on link Li, and the incremental bandwidth that needs to be reserved is Bp-Br(i). If, however, Bp is greater than the total capacity of the link, then the link cannot be used to protect the service, and the cost of link Li is preferably set to a sufficiently high value to exclude this link and, in fact, this entire candidate restoration path, from further consideration as a restoration path for this service on this primary path. Alternatively, this "total capacity" constraint may be applied to exclude such paths from being included when the set of candidate restoration paths is originally generated.

[0209] (c) Sharing possible—scenario B: Finally, if the intersection I-Li-set between B-Li-set and P-set is non-null, then the intersection indicates which links of the candidate primary path are already protected by link Li for other primary paths. If a link Lk (from I-Li-set) is already protected by link Li, then the total amount of bandwidth that will need to be reserved on link Li to protect against a failure of link Lk is at least the amount of protection bandwidth Bk needed on link Li to protect other services on link Lk plus the bandwidth Bp of the new service. There are again two cases.

[0210] In the first case, the bandwidth Br(i) that is presently reserved on link Li is greater than or equal to Bp+Bk for all links Lk in I-Li-set. In this case, no additional bandwidth need be reserved to protect the new service, and the cost of using this link of the candidate restoration path is zero.

[0211] In the second case, Bp+Bk is greater than the presently reserved bandwidth on link Li for at least one link Lk in I-Li-set, and the incremental bandwidth that needs to be reserved is $Bp+\max(Bk)|_k-Br$. If, however, $Bp+\max(Bk)|_k$ is greater than the total capacity of the link, then, the link cannot be used to protect the service and the cost of link Li should be set to a sufficiently high value to exclude this link and, in fact, this entire candidate restoration path, from further consideration as a restoration path for this service on the considered primary path.

[0212] The above information is consolidated into an exemplary procedure for determining a minimum-cost restoration path given a particular primary path as illustrated by **FIG. 15**. As shown, in step **1500**, a primary path is selected for a new service of bandwidth Bp, and the set of links P-set on that primary path is initialized. Next, in step **1502**, N candidate restoration paths are chosen from amongst the possible alternative paths in the network that are disjoint from the primary path. In step **1504**, restoration path index j is initialized to zero, and the variables Lowest_Cost and BestRPathID are initialized to a sufficiently high value (e.g., infinity) and 0, respectively. Next, in step **1506**, the cost Cost_Rj of the restoration path is calculated as a sum of the costs of its constituent links (more detail is shown in **FIG. 16** described below), and the calculated Cost_Rj is compared with the current value of Lowest_Cost in the test of step **1508**.

[0213] If Cost_Rj is less than Lowest_Cost, then, in step **1510**, Lowest_Cost is set equal to Cost_Rj, and BestRPathID is set equal to restoration path index j. Next, or if the test of step **1508** fails, in step **1512**, index j is incremented, and the test of step **1514** is then performed to determine whether all the candidate restoration paths have been considered. If they have, then the procedure finishes in step **1516**. If they have not, then the procedure continues with the calculation of the cost of the next candidate restoration path in step **1506**.

[0214] **FIG. 16** illustrates an exemplary procedure for calculating the cost of each restoration path Rj per step **1506** of **FIG. 15**. The procedure begins in step **1600** with the initialization of Rj-set={links in candidate restoration path Rj}. Next, in step **1602**, for each link Li in Rj-set, B-Li-set={links protected by Li}. Note that this protection information is stored locally, centrally, or in distributed fashion at one or more nodes in the network and may be communicated completely or incrementally and stored via one or more of the mechanisms discussed elsewhere in this specification

(e.g., OSPF flooding mechanism and OSPF opaque LSA and TE/Share database). In step **1604**, for each link Li, I-Li-set={intersection of B-Li-Set and P-set}. Next, in step **1606**, link index i and variable Cost_Rj are initialized to zero, and, in step **1608**, index i is incremented.

[**0215**] In step **1610**, a test is done to see if B-Li-set is null indicating the lack of any sharing potential in link Li. If the set is null, then, in step **1612**, Cost_Li is set equal to the bandwidth Bp of the primary path. Otherwise, in step **1614**, as test is performed to determine whether the intersection set I-Li-set is null indicating no common links between the primary path and those links being protected by link Li.

[**0216**] If the intersection set is null, then, in step **1616**, Cost_Li is set equal to the maximum of either zero or the result of subtracting the bandwidth Br(i) that is already reserved on link Li from the bandwidth Bp of the new primary path service. If the intersection is non-null, then, in step **1618**, Cost_Li is set equal to the maximum of zero and $Bp+\max|_k(Bk)-Br(i)$.

[**0217**] Following steps **1612**, **1616**, or **1618**, the test of step **1620** is performed to determine whether the additional bandwidth, if any, required on link Li exceeds the available capacity of link Li. If it does, then, in step **1622**, Cost Rj is set to a sufficiently high value (e.g., infinity), and the procedure exits in step **1624**. Otherwise, in step **1626**, the cost of the current link is added to the current cost of the restoration path, and the procedure continues to step **1628**, which determines whether all of the links in the current protection path Rj have been considered. If not, then the processing returns to step **1608**; otherwise, processing exits at step **1624**.

[**0218**] As an example, consider the partial network **1700** of **FIG. 17**. Consider the primary path L**1**-L**2** with four units of bandwidth. Also, assume that there are two possible disjoint routes (with respect to the primary path) to the destination, namely route A (L**3**-L**4**) and route B (L**5**-L**6**). Further, assume that the entries of the current TE/Share database (DB) are as shown below:

[**0219**] Entry for L**3** in TE/Share DB→4::L**1**, L**8**; 5::L**10**

[**0220**] Entry for L**4** in TE/Share DB→4::L**8**, L**9**

[**0221**] Entry for L**5** in TE/Share DB→4::L**9**, L**10**

[**0222**] Entry for L**6** in TE/Share DB→4: :L**8**, L**10**

[**0223**] The P-set for this example is {L**1**, L**2**}, the first R-set, R_A-set={L**3**, L**4**} and the second R-set, RB-set={L**5**, L**6**}. The B-Li-sets for restoration path A are B-L**3**-set={L**1**, L**8**, L**10**} and B-L**4**-set={L**8**, L**9**}. Similarly, the B-Li-sets for restoration path B are B-L**5**-set={L**9**, L**10**}, B-L**6**-set={L**8**, L**10**}. Evaluating the first restoration path, it is noted that none of the B-Li-sets are null, thus each of the links within the first restoration path offers some potential for sharing. Here, for example, the entry for link L**3** indicates that L**3** needs to reserve four units of bandwidth to protect L**1** and L**8** and five units of bandwidth to protect L**10**. Note that links L**8**, L**9**, and L**10** are outside of the partial network **1700** shown in **FIG. 17**, but are still considered in the above example to levy protection requirements on the links as indicated below. Note that the actual reserved bandwidth on link L**3** would be the maximum of those two bandwidths, namely five units. Similarly, the entry for L**4** indicates that L**4** needs to reserve four units of bandwidth to protect against failures on L**8** and L**9**. The entries for links L**5** and L**6** are interpreted similarly.

[**0224**] In operation, source node R**1** would compare the primary path L**1**-L**2** against the entries for every link in a restoration path (e.g., R_A-set={L**3**, L**4**}) and repeat the comparison for all possible restoration paths (e.g., R_A-set and R_B-set). Upon comparison with path L**3**-L**4**, it is found that link L**1** is already shared and that, if node R**1** were to choose this restoration path, then the reservation bandwidth on L**3** would need to be increased by 3 (i.e., 4+4−5) additional units of bandwidth. However, no additional bandwidth would need to be reserved on L**4**.

[**0225**] Upon comparison with restoration path L**5**-L**6**, it is found that the intersection of P-set {L**1**, L**2**} and R_B-set {L**8**, L**9**, L**10**} is null, and no additional units of bandwidth would need to be reserved (since 4 units have been reserved already). Therefore, under such circumstances, the restoration path L**5**-L**6** would be considered to be the better restoration path.

[**0226**] On the other hand, if the entries corresponding to L**3** and L**4** remain unaltered, but those corresponding to L**5** and L**6** have changed to those below:

[**0227**] Entry for L**5** in TE/Share DB→1::L**9**, L**10**

[**0228**] Entry for L**6** in TE/Share DB→1::L**8**, L**10** then it can be seen that choosing restoration path L**5**, L**6** would require a total of six additional units of bandwidth (i.e., three additional units for each of links L**5** and L**6**) to support a primary path of four units of bandwidth. In this case, path L**3**-L**4** is a better choice for restoration since only a total of three additional units of bandwidth need to be reserved in the network.

[**0229**] LSA Formats for Sharing

[**0230**] The Shared Restoration LSA starts with the standard LSA header. The LSA payload includes one or more nested Type/Length/Value (TLV) triplets for extensibility. The Length field defines the length of the value portion in octets (a TLV with no value portion would have a length of zero). The TLV is padded to a four-octet alignment. Padding is not included in the length field (so a three octet value would have a length of three, but the total size of the TLV would be eight octets). Nested TLVs are also 32-bit aligned. Unrecognized types are ignored. All types between 32,768 and 65,535 are reserved for vendor-specific extensions. All other undefined type codes are reserved for future assignment by the Internet Assigned Number Authority (IANA). A Shared Restoration LSA contains one top-level TLV. The Restoration TLV describes a single link of the advertising node. Only one Restoration TLV is be carried in each LSA. The Link TLV is type 1; the length is variable and describes the length of the value field. The Link Type (1 octet), Local Interface Index (4 octets), and Local Interface IP Address (4 octets) should be non-zero, while the value of the reserved field should be zero and is reserved for future use. All other fields defined are present conditional to the value of the Resource Flag field.

[**0231**] The Link Type field defines the type of the link: 1 implies point-to-point, 2 implies multi-access. The Local Interface IP Address field specifies the IP address of the interface corresponding to this link. This field is 4 octets in

length. The format described supports IPV4 addressing, and the reserved fields can accommodate IPV6. The Reserved field can be used to specify this, and the length of the TLV can be appropriately increased. The first octet of the value field, the Resource Flag, describes the kind of resources that follow. If Resource Flag is set to 0×01, only the restoration bandwidth and the maximum restoration bandwidth are present, where restoration bandwidth is the currently allocated restoration bandwidth on that link and the maximum restoration bandwidth is the maximum amount of restoration bandwidth allowed on that link. Both the Restoration Bandwidth and the Maximum Restoration Bandwidth fields are expressed in IEEE floating-point format and specified in bytes.

[0232] If the Resource Flag is set to 0×10, then the Restoration Bandwidth and the Maximum Restoration Bandwidth fields are absent. What follows in the LSA are the various primary links that this link provides restoration for, and the bandwidth on each of them. The Bandwidth field describes the amount of bandwidth in IEEE format, in bytes. The Primary Links fields following the Bandwidth field are the primary links for which this link provides restoration, and whose bandwidth on each of them is specified by the Bandwidth field. Once again, only IPV4 addresses are illustrated. The Reserved field may be used in the future to indicate IPV6 addresses. The Number of Primary Links field describes the number of primary links that follow the Bandwidth field.

[0233] If the Resource Flag is set to 0×20, once again the Restoration Bandwidth and Maximum Restoration Bandwidth fields are absent. What follows in the LSA are the various primary links that this link provides restoration for. This case is similar to the case when Resource Flag is set to 0×10, except that this case addresses the issue of finding bandwidth sharing, rather than the actual amount of bandwidth that is shared. In a way, this is a binary form of the previous case, wherein the problem of "can sharing be done" is addressed in a true-or-false form. Once again, all IP addresses are IPV4, and the Reserved field may be used in the future to indicate IPV6 addresses.

[0234] Cases where the Resource Flag is set to 0×11 and 0×21 are similar to cases 0×10 and 0×20, respectively. However, the Restoration Bandwidth and the Maximum Restoration Bandwidth fields are also present. Note that, with Resource Flag set to 0×11 , the source node would have detailed information about the constraint and degree of sharing of link restoration bandwidths during the computation of restoration path. Use of other modes trades away the network utilization with less information for advertisement and local bookkeeping.

[0235] A summary of one possible structure of link-state advertisement per opaque LSA extensions is as follows:

[0236] Fields: Intf|N-id|Flag|AW|LC|AC|D|U-SN|Len|Rid|Rid|. . . |Rid |

[0237] where the fields in the LSA are as follows:

[0238] Intf—the interface number (in its node) of this link (16 bits)

[0239] N-id—the neighbor's IP address (32 bits)

[0240] Flag—determines what follows in the rest of the LSA

[0241] AW—the administrative weight of the link (16 bits)

[0242] LC—the bandwidth capacity of the link (16 bits)

[0243] AC—the bandwidth that is actually available for use (24 bits)

[0244] U-SN—the update sequence number (32 bits)

[0245] Len—number of Rid that follows in this LSA (8 bits)

[0246] Rid—id of a node, for which the binary node vector value is 1 (32 bits)

[0247] Advertising only non-zero elements of the node-binary vector can reduce significantly the amount of the advertised data

[0248] Use and Handling of the Shared Restoration LSAs

[0249] Nodes originate Shared Restoration LSAs whenever the TE/Share database changes and whenever otherwise indicated by OSPF (an LSA refresh, for example). Upon receipt of a changed Shared Restoration LSA, a node will update its TE/Share database. No shortest path first (SPF) or other route calculations are necessary. Interoperability with nodes that do not implement the extensions should not have problems interoperating with those that do, as the Opaque LSAs will be silently ignored. The result, however, will be that the network might not be able to utilize the resource as efficiently and may fail to find a restoration path when there is a viable one.

[0250] Reservation of the Protection Capacity Pool

[0251] The protection capacity reserved on a given link is also known as a capacity pool because it may be shared among multiple paths for protection purposes. In the embodiment of SMDN **100** of **FIG. 1**, this pool may be either statically provisioned or dynamically assigned. In both cases, an MPLS switch located at each node in the SMDN is capable of setting aside capacity on each of its connected links without actually allocating it to any LSPs. In practice, each protection LSP is set up with zero or some minimum bandwidth to support operation, administration, and maintenance (OAM) packets associated with the protection signaling of the network. This bandwidth is typically smaller than the bandwidth reserved to protect the primary LSP traffic.

[0252] In case of static provisioning, a pool of bandwidth on each link is set aside in advance of service provisioning specifically for the purpose of recovering traffic affected by a failure. If the amount of protection bandwidth is known in advance, then static allocation becomes an option. For example, in the case where the SMDN to be protected has a ring topology, half of the available network bandwidth might be statically allocated in advance as the protection bandwidth. Independent of what combination of services of different bandwidths get added to the working half of the bandwidth, the protection half of the bandwidth should be sufficient to protect all working traffic affected by a single link or node failure in the network. By using static allocation, in applying shared mesh protection methodology, bookkeeping is minimized. The call admission control (i.e., the process that accepts a new call or data communication request into the network) for the working traffic (LSP) typically will only admit those calls that will be sufficiently

protected by the available bandwidth along the protection path (given at most a single failure in the network).

[0253] In the case of dynamic assignment, the size of the protection pool (i.e., the protection bandwidth reserved on each link of the network) may dynamically expand or shrink based on the protection needs of the network as new connections (LSPs) are being admitted or established, and existing connections (LSPs) are being removed, respectively. Thus, dynamic assignment provides flexibility to adapt the protection to changes in the traffic.

[0254] In a distributed implementation of the shared mesh data network, when sharing information is distributed across the nodes in the network, each node along a new protection path computes the amount of additional protection bandwidth it might need on its downstream connected link along the new protection path to protect a corresponding new primary LSP. For additional protection bandwidth, a node first checks for the availability of the additional bandwidth on the connected link, and, if the additional bandwidth is available, then the node adds the additional bandwidth to the reserve protection pool of the connected link that is downstream of the node along the protection path.

[0255] In case of the centralized server approach, a centralized server computes the additional protection bandwidth needed on each link along the protection path to admit a new connection (LSP). This information is then conveyed as part of network signaling to establish the protection LSP.

[0256] Fast Failure Detection and Notification

[0257] As in other asynchronous transport networks, an SMDN that incorporates MPLS for traffic engineering might suffer from uncertainty and potentially unbounded delay in the delivery of packets. This sometimes makes it more difficult to achieve fast failure detection and notification. This is because a failure might not be detected by monitoring just the absence of packet arrivals at a destination. Specifically, there may be ambiguity in distinguishing between the absence of packets due to a failure of an LSP and the absence of traffic on the LSP due to a lull in communication between the source and destination. Therefore, to achieve fast failure detection, in certain implementations of an SMDN that utilizes MPLS for traffic engineering, any of four alternative approaches might be used.

[0258] In the first approach, failure detection relies on the physical transport (optical layer) to detect and propagate failure indications up into the MPLS layer. In this approach, every node in the network is assumed to be capable of propagating failure indications downstream by inserting forward-defect-indicator operations-and-maintenance (FDI-OAM) packets into the flow of traffic. More details on OAM and FDI-OAM in MPLS networks can be found in ITU-T Recommendation Y.1711, "OAM mechanism for MPLS networks," Nov. 2002 (herein Y.1711), incorporated herein by reference in its entirety. In this approach, as soon as a node that is downstream from a physical-layer failure detects the failure, it inserts FDI-OAM packets carrying the failure indication in all affected LSPs passing through it. Note that these FDI-OAM packets are inserted in-band in the downstream direction. The destination node of each of the affected primary paths will ultimately receive these special OAM packets. Upon receiving this in-band failure notification, the destination passes the failure information to the source of the affected LSP using backward-defect-indicator OAM (BDI-OAM) packets (also defined in Y.1711). Note that a failure indication from the destination to the source is passed using a pre-established LSP that is disjoint from the failed primary LSP.

[0259] Using this first approach, the SMDN can recover quickly (e.g., on the order of tens of milliseconds) from failures that are detectable at the optical layer. However, there may be other failures above the optical layer that can cause failure of LSPs. Since these failures might not be detectable at the optical layer, optical-layer detection alone might not provide full coverage for failure monitoring of MPLS paths (LSPs).

[0260] In a second approach, failure detection and protection at the LSP level can be achieved by periodically inserting special OAM packets, known as fast failure detection (FFD) packets, into the primary LSPs of the SMDN. When a working LSP is provisioned, the source node of the LSP is configured to generate and insert FFD-OAM packets periodically into the LSP with a time interval T. At the receiver side, the arrival of FFD-OAM packets is continuously monitored. The receiver registers a failure on the LSP when it does not see any FFD-OAM packets on the LSP for an interval of nT, where n is a configurable integer value ($n \geqq 1$). Note that a larger value of n reduces false failure detection probability.

[0261] False failure detection occurs when packet delays or loss of FFD-OAM packets (rather than a true connection failure) result in incorrect declaration of an LSP failure. This problem can be addressed within the packet quality-of-service (QoS) framework. For example, one can mark the label of these packets in such a way that these packets are treated with high priority in scheduling and buffer management at each label-switched node within each node of the LSP. Consequently, delay jitters and dropping of FFD-OAM packets are minimized. QoS prioritization can also be applied to FDI-OAM and BDI-OAM packets to improve performance of the first approach, which was based on failure indication at the optical-transport layer.

[0262] In a third approach, the source node of an LSP inserts FFD-OAM packets when the LSP is idle. Specifically, when the LSP is idle for more than a specified time interval T, an FFD-OAM packet is inserted and sent to the destination node. The destination node will declare a failure of the LSP when the LSP is in the idle state for an interval greater than nT where n and T are provisionable parameters of the network. The value of n should be selected such that false failure detection probability is minimized.

[0263] Finally, in a fourth approach, a combination of an optical-layer detection mechanism (e.g., the first approach) and a higher-level MPLS-layer detection mechanism (e.g., the second or third approach) is used to achieve fast and comprehensive failure coverage and recovery.

[0264] Assigning Reserve Capacity to Protection LSPs

[0265] It is assumed that every protection LSP is established with an assigned bandwidth of zero or some minimal value sufficient to carry OAM traffic. After a failure, traffic coming into the ingress node for a primary LSP is switched to its corresponding protection LSP, and traffic exiting the egress node for the primary LSP is selected from the protection LSP, instead of from the primary LSP. The

aggregate bandwidth for the protected traffic on primary LSPs is reserved in advance as part of the protection pool in the SMDN. Note that the bandwidth of the protection pool is not reassigned to any protection LSP. After the failure, each protection LSP that is providing protection against a specific failure needs to be assigned the same bandwidth and QoS characteristics as were assigned to the primary LSP it protects. This requires changing the bandwidth assignment of each of these protection LSPs. This can be accomplished through RSVP-TE using its bandwidth change procedure (see RFC 3209 for details).

[0266] Switching Between Working and Protection LSPs

[0267] As discussed above, after detecting a failure, end nodes of an LSP switch traffic from a primary (i.e., working) LSP to its corresponding protection LSP. Note that both working and protection LSPs typically enter the ingress node and exit the egress node using different ports.

[0268] At the ingress node, this may be accomplished by the node maintaining two different next-hop label-forwarding entry (NHLFE) entries in the MPLS forwarding equivalence class-to-NHLFE (FEC-to-NHLFE or FTN) map (one for the working path and the other for protection path) and activating only one of these at a time. Since the FTN is used to map incoming client packets to an NHLFE, activating one or the other of these entries will serve to direct packets coming into an ingress node to the working or the protection path, effectively switching between working and protection LSPs. Thus, protection switching on ingress involves switching from the working to the protection NHLFE.

[0269] On the egress node, there is a separate NHLFE entry for working and protection LSPs dictating the next action. Based on the label (for a switch-wide label-space implementation) or combination of port and label (for a port-based label-space implementation) that the packet carries, the proper entry is chosen and correspondingly the next action/operation (e.g., pop the label and pass the payload to the client layer) (see RFC 3031) is dictated by the entry for the packet. Thus, no specific switching really needs to be performed at the egress node since the action has the effect of delivering the data from the proper path (e.g., primary or protection) to the client. Note that both entries normally dictate the same next action.

[0270] Functional Architecture

[0271] An SMDN can be partitioned into a variety of modules. These modules are part of a network manager that may be implemented at a centralized server or distributed partially or fully to the nodes. Some exemplary modules, representing one specific functional partitioning of the components of an SMDN, which provide functionality such as fault detection and notification, protection switching, signaling and control, routing, and OAM, are listed below:

[0272] Service Agent (SA): This module provides interface to application or service management for provisioning paths with different restoration/QoS requirements.

[0273] Path Management (PM): This module primarily consists of the signaling protocol such as RSVP-TE. It is responsible for path setup, refresh, teardown, and monitoring functions.

[0274] Path Computation (PC): This module provides path computation services to the path management module. It interfaces with the link-state-based routing protocol to obtain the network topology.

[0275] Network Topology (NT): This module primarily consists of the link-state-based routing protocol. It is responsible for monitoring and updating of network topology.

[0276] Fault Detection (FD): This module provides the fault detection capability. Faults can be detected through monitoring of layer-1, layer-2, and layer-3.

[0277] Fault Notification (FN): This module is responsible for notifying protection switching nodes of detected faults.

[0278] Protection Switching (PS): This module is responsible for switching the affected traffic onto a protection LSP after detecting a failure or receiving failure notification.

[0279] OAM&P (OAM): This module is responsible for providing performance monitoring functions on a per-LSP basis through use of special OAM&P packets. It can help in detecting any faults affecting the MPLS shim-layer.

[0280] Bandwidth-Sharing Information (BSI): This module is responsible for managing the sharing of information related to protection sharing in the SMDN. It provides functionality at each node to keep track of the sharing status at each of the incident links to that node. This module works in conjunction with the PM module, which uses special signaling to carry working path information (bandwidth, nodes, and links) along the protection path in the SMDN. This information is required to keep bandwidth-sharing information current.

[0281] These functional modules can be classified into two groups. The first group includes those functional modules that support a manually provisioned shared mesh protection service. This set includes the FD, FN, PS, and OAM modules. The second group includes modules that bring automation to resource discovery, path computation, and path establishment and management. These modules can perform signaling and control plane functions. They include the SA, PM, PC, and NT modules.

[0282] **FIGS. 18, 19**, and **20** illustrate the functionality of the ingress, intermediate, and egress nodes, respectively, of the SMDN. These figures collectively illustrate a distributed implementation of the path computation function of SMDN **100** of **FIG. 1**. In contrast to the illustrated implementation, in a centralized implementation, path computation and sharing information functions would reside on a centralized server.

[0283] Ingress, Intermediate, and Egress Nodes

[0284] **FIGS. 18, 19**, and **20** depict the interrelationship of the subset of modules that comprise ingress, intermediate, and egress node operations of the nodes within an SMDN according to one embodiment of the present invention. Note that, typically, any node within an SMDN may at one time or another, for one service or another, serve as an ingress node, an intermediate node, or an egress node, or simulta-

neously as two or more of ingress, intermediate, or egress nodes. Therefore, **FIGS. 18, 19**, and **20** do not necessarily depict unique nodes in the SMDN, but rather highlight the relevant functions of a node that are associated with its operation as ingress, intermediate, or egress with respect to a particular LSP.

[**0285**] The function of each of the modules was described in the previous section. To complement those descriptions, the role of each of the modules in each of these nodes is described herein with respect to the exemplary establishment of a new service. For clarity, this example will parallel the example provided earlier of the addition of LSP-**11** (working) and LSP-**12** (protection) to SMDN **100** of **FIG. 1**.

[**0286**] To begin, a service request is received at node N**4** of **FIG. 1** for the establishment of an LSP between N**4** and N**2** of SMDN **100**. Assume that, at the arrival of the request, the network was in a state captured by **FIG. 1** and TABLE **1** of **FIG. 2**. Referring to **FIG. 18**, the service request is received and serviced by service agent (SA) **1802** of ingress node **1800** via either user network interface (UNI) or simple network management protocol (SNMP) signaling. Details on SNMP and ATM UNI can be found in RFC2570 and The ATM Forum, "ATM User Network Interface (UNI) version 4.1," Nov 2002 (herein "UNI4.1"), each incorporated herein by reference in its entirety. The SA provides a translation between the application-layer request for the service and path management (PM) function **1804**, which is responsible for the establishment and monitoring of the health of the LSP and its protection path. As illustrated, the PM includes glue logic **1806** and standard and extended signaling components **1808**. Glue logic **1806** allows the PM to interface with various other modules within the node that it needs to communicate with to accomplish its task, while signaling sub-module **1808** allows the PM to communicate information about the new paths to other nodes in the SMDN.

[**0287**] Specifically, glue logic **1806** allows the PM to communicate with path computation (PC) module **1812** to determine two suitable disjoint (if possible) paths for working and protection LSPs. The PC in turn interfaces to network topology (NT) module **1818** to gather current topology information (e.g., via link-state architecture (LSA) messages) used in the path computation. In this example, it can be assumed that PC **1812** returned the disjoint paths (N**4**-L**3**-N**5**-L**4**-N**2**) and (N**4**-L**1**-N**1**-L**2**-N**2**) to PM (possibly among other disjoint pairs) to consider as working and protection paths for the newly requested service.

[**0288**] Glue logic **1806** also allows the PM to communicate with bandwidth-sharing information (BSI) module **1810**. The BSI module is responsible for managing the sharing of information related to protection in the SMDN associated with LPS-**11** and LSP-**12**. Its function in N**4** is to keep track of the sharing status at each of the incident links to N**4** (namely L**1** and L**3**). Thus, it does the bookkeeping for sharing for N**4** and thus maintains the information corresponding to rows L**1** and L**3** of TABLE **1** (and, after update, TABLE **2** of **FIG. 3**). The BSI is also responsible for providing the PM with working-path information that it needs to share (along the protection path of the new LSP) to keep the network up-to-date with the sharing information.

[**0289**] The PM also interfaces via glue logic **1806** to protection switching (PS) module **1814** to indicate by which path (working or protection) incoming traffic will exit N**4**. As discussed before, this may be implemented by activating one or another of the two NHLFE entries in the (FTN) map (represented here by PS sub-module NHLFE **1816**). During the creation of a service, the traffic is mapped to the NHLFE entry corresponding to the working LSP. The entry selection decision (and consequently the choice of working or protection path) may be overridden by information (e.g., via BDI-OAM packets) received via OAM module **1820** indicating a failure somewhere along the downstream working path, in which case the traffic mapping is switched to the other NHLFE entry corresponding to the protection LSP. Note that this switching of traffic between working and protection can also be forced via a network management command. OAM **1820** also functions to insert OAM packets (e.g., FFD-OAM and FDI-OAM) into the working and protection paths to support monitoring and failure detections in the SMDN.

[**0290**] Referring next to **FIG. 19**, labels **1902** and **1904** refer to functional modules that are active in an intermediate node along the working path and the protection path, respectively, of the SMDN. With respect to the present example, module **1902** depicts the operation of a node (e.g., N**5**) that is along working path LSP-**11**, and module **1904** depicts the operation of a node (e.g., N**1**) that is along protection path LSP-**12**.

[**0291**] As illustrated by module **1902**, the PM in a working path intermediate node relays standard signaling along the path and directs incoming label-switched traffic to the next hop along the working path as indicated by the active entry (NHLFE) in the local incoming label map (ILM). If necessary (e.g., if a failure is detected), the local OAM function may insert FDI-OAM packets into relevant LSPs to support monitoring and failure detection in the SMDN.

[**0292**] As illustrated by module **1904**, the PM in a protection path intermediate node performs similarly to the PM in the working path intermediate node but has some additional active modules as well. Namely, extended-signaling functions within the PM allow for the receipt of sharing information about the working path to be communicated via the glue logic to the local BSI module. As in the ingress node, the BSI will maintain and update sharing information associated with the node's incident links. For example, if module **1904** represents the active modules in intermediate node N**1** along LSP-**12**, then it will store the sharing information corresponding to its incident links L**1** and L**2**, namely rows L**1** and L**2** of TABLE **1** (and, after the establishment of the new LSP, rows L**1** and L**2** of TABLE **2**).

[**0293**] Finally, in an egress node (illustrated by exemplary node **2000** of **FIG. 20**), the PM serves as a terminal point in the LSP signaling chain for both standard and extended signaling. It also interfaces to the PS to configure the two NHLFE entries corresponding to working and protection LSPs. The incoming label selects the NHLFE entry that, as discussed before, dictates the next action on the packet. In this case, NHLFE traffic is extracted (corresponding to which path is actively carrying traffic) and passed on to the node-attached client packet. In the case of penultimate hop popping, there might not be an NHLFE at the egress node. In this case, the previous node pops the label and the next operation is implicitly derived from the packet itself (for example, Internet protocol (IP) will be used to route the IP packet). An OAM module in the egress node extracts OAM

packets from each LSP and inserts them in the corresponding LSPs in the reverse direction to support monitoring and failure detection and recovery in the SMDN.

[0294] While the embodiments of this invention have been discussed with respect to protection, they may equally well be applied to restoration, with the assumption that some or all of the calculations associated with paths are calculated after the detection of a failure.

[0295] While this invention has been described with respect to protection associated with situations where the protection was directed to single-point failures, the concepts, and, in particular, the link-state description, may be extended to multiple-point failure situations.

[0296] While various calculations within this invention have been described with respect to unit bandwidth services, these calculations could equally well be applied to non-unit bandwidth services, (e.g., by equating non-unit bandwidth services to an equivalent number of unit-bandwidth services) as would be understood to one skilled in the art.

[0297] While this invention has been described with respect to dissemination of sharing information by specific mechanisms including OSPF, alternative means for dissemination of information within mesh networks could also be used (e.g., RSVP-TE, TCP/IP connections, constrained routing label distribution protocol (CR-LDP)), and SNMP) as would be understood to one skilled in the art.

[0298] While aspects of this invention has been described in one or more embodiments in the context of mesh data networks running one or more of the multiprotocol-label switched (MPLS) traffic engineering extension protocols, those aspects are equally applicable to a wide class of networks where traffic engineering is supported, these networks classified as providing virtual-circuit services, as would be understood to one skilled in the art.

[0299] Note that, in one or more embodiments of the present invention, a node is assumed to have the intelligence for computations associated with aspects of the invention (e.g., for determining sharing, and calculating and reserving restoration bandwidth on links), however, as would be understood to one skilled in the art, a regional manager that supports one or more nodes can be substituted for the node's intelligence while remaining within the spirit and intent of the present invention. In this document, it should be understood that, in some cases, the regional manager may manage only a single node and be hosted by that node.

[0300] While this invention has been described with reference to illustrative embodiments, this description should not be construed in a limiting sense. Various modifications of the described embodiments, as well as other embodiments of the invention, which are apparent to persons skilled in the art to which the invention pertains are deemed to lie within the principle and scope of the invention as expressed in the following claims.

[0301] Although the steps in the following method claims, if any, are recited in a particular sequence with corresponding labeling, unless the claim recitations otherwise imply a particular sequence for implementing some or all of those steps, those steps are not necessarily intended to be limited to being implemented in that particular sequence.

What is claimed is:

1. A method for determining primary and restoration paths for a new service in a mesh network having a plurality of nodes interconnected by a plurality of links, the method comprising:

for each of a plurality of candidate path pairs for the new service, each candidate path pair comprising a candidate primary path and a candidate restoration path for the new service, generating a path cost associated with said each candidate path pair, wherein the path cost for a candidate path pair is a function of sharability of links within the corresponding candidate restoration path; and

selecting the primary and restoration paths for the new service from the plurality of candidate path pairs based on the path cost of each candidate path pair.

2. The invention of claim 1, wherein generating the path cost for each candidate path pair comprises:

generating a link cost associated with each link in the corresponding candidate restoration path; and

generating the path cost as a function of a sum of the link costs for all links in the candidate restoration path.

3. The invention of claim 2, wherein, for each link, generating the link cost comprises:

determining whether sharing is available on the link; and

if sharing is available, then generating the link cost as a function of a sharing degree for the link.

4. The invention of claim 3, wherein, if sharing is not available, then:

determining whether utilization of the link is greater than a specified threshold;

if the link utilization is greater than the specified threshold, then generating the link cost as a function of an administrative weight for the link and available capacity on the link; and

if the link utilization is less than the specified threshold, then generating the link cost as a function of the administrative weight for the link.

5. The invention of claim 3, wherein the link cost is also generated as a function of an administrative weight for the link.

6. The invention of claim 3, wherein the link cost is also generated as a function of a form of a sharing degree.

7. Then invention of claim 6, wherein the form of the sharing degree is an approximation to the sharing degree that is calculated using a binary representation of a node-link vector and a binary representation of a primary path node-link vector, wherein the calculation of the approximation comprises:

computing the bitwise AND of the binary representation of the node-link vector and the binary representation of the primary path node-link vector, and

computing the OR of all elements of the resulting vector to determine whether sharing is possible.

8. The invention of claim 1, wherein the sharability of a link in a candidate restoration path is represented by a sharing degree for the link, wherein the sharing degree is a maximum number of additional unit-bandwidth primary services that can be added to the candidate primary path without increasing restoration bandwidth reserved on the link.

9. The invention of claim 8, wherein the sharing degree SD for a link is given by:

$$SD=\text{the maximum value m for which max } \{m\cdot V_{pnl}+V_{nla}\}=RB,$$

wherein:

V_{pnl} is a primary path node-link vector for the corresponding candidate primary path;

V_{nla} is an aggregate node-link vector for the link; and

RB is current reservation bandwidth on the link.

10. The invention of claim 8, wherein the sharing degree SD for a link is given by:

$$SD=\text{the maximum value m for which max } \{m\cdot V_{pn}+V_{na}\}=RB,$$

wherein:

V_{pn} is a primary path node vector for the corresponding candidate primary path;

V_{na} is a node-aggregate vector for the link; and

RB is current reservation bandwidth on the link.

11. A network manager for a mesh network having a plurality of nodes interconnected by a plurality of links, the network manager adapted to determine primary and restoration paths for a new service in a mesh network, wherein:

for each of a plurality of candidate path pairs for the new service, each candidate path pair comprising a candidate primary path and a candidate restoration path for the new service, the network manager is adapted to generate a path cost associated with said each candidate path pair, wherein the path cost for a candidate path pair is a function of sharability of links within the corresponding candidate restoration path; and

the network manager is adapted to select the primary and restoration paths for the new service from the plurality of candidate path pairs based on the path cost of each candidate path pair.

12. The invention of claim 11, wherein the network manager is distributed over the network.

13. The invention of claim 11, wherein the network manager is located at a single node of the network.

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