Demonstration of the Highly Reliable HIKARI Router Network Based on a Newly Developed Disjoint Path Selection Scheme

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ABSTRACT

Integration of multiprotocol label switching functions and multiprotocol lambda switching functions can enhance the throughput of IP networks and remove bottlenecks that are derived from electrical packet processing. To enhance the packet forwarding capability, NTT proposed a photonic MPLS concept that includes MPλS, and demonstrated IP, MPLS, and photonic MPLS integrated router systems called the photonic MPLS router. This router system is now called the HIKARI router. The word HIKARI is Japanese meaning beam, light, lightwave, optical, photonic, and sunshine. The amount of IP data traffic has grown remarkably. Massive IP routers and flexible route control mechanisms are now required to cope with the increased amount of traffic. The HIKARI router can offer two solutions utilizing photonic switching technologies, and photonic network operation and management technologies. The first solution is utilizing photonic switching technologies realized using optical-switch-based crossconnect systems. The other solution is realized using the MPLS and MPλS signaling protocol and photonic network protection functions. In this article we report on the implementation of the HIKARI router systems, propose a newly developed disjoint path selection scheme for generalized MPLS networks with shared risk link group constraints, and demonstrate the signaling protocol and network protection functions. The demonstration system achieves a distributed optical path set-up/tear-down protocol with an extended Constraint-Based Routing Label Distribution Protocol. Fast self-healing through automatic protection switching and a new restoration scheme are also implemented. These functions are successfully implemented, and the performance is verified on a demonstration network. The protection switching scheme achieves protection in less than 20 ms, and the optical path restoration scheme achieves restoration in less than 500 ms.

INTRODUCTION

The amount of IP data traffic has grown remarkably over the past few years. Massive routers and flexible route control mechanisms are required to help deal with this growth, and optical technology must catch up with this trend.

From the viewpoint of network control, multiprotocol label switching (MPLS) [1] has shown great promise as a solution to the growth in traffic. MPLS was initiated on the control plane of cell- or frame-based systems such as asynchronous transfer mode (ATM), frame relay, Ethernet, and Point-to-Point Protocol/High-Level Data Link Control (PPP/HDLC). A few years ago, some proposals were submitted pertaining to the MPLS control capability on optical networks, such as multiprotocol lambda switching (MPλS) [2] and photonic MPLS [3]. These issues have become topics of intense discussion and have been broadened to generalized MPLS (GMPLS) [4], which is still under discussion in many standardization bodies, such as the Internet Engineering Task Force (IETF), International Telecommunication Union — Telecommunication Standardization Sector (ITU-T), and Optical Internetworking Forum (OIF). In order to realize an MPλS prototype, two fundamental modifications are required between MPλS and MPLS. The first is that the relationships between the label values and wavelength numbers must be defined. This will lead to fewer labels used in MPλS than in MPLS due to the limitations in physical wavelength-division multiplexing (WDM) transmission characteristics. In the MPλS case, there is a one-to-one

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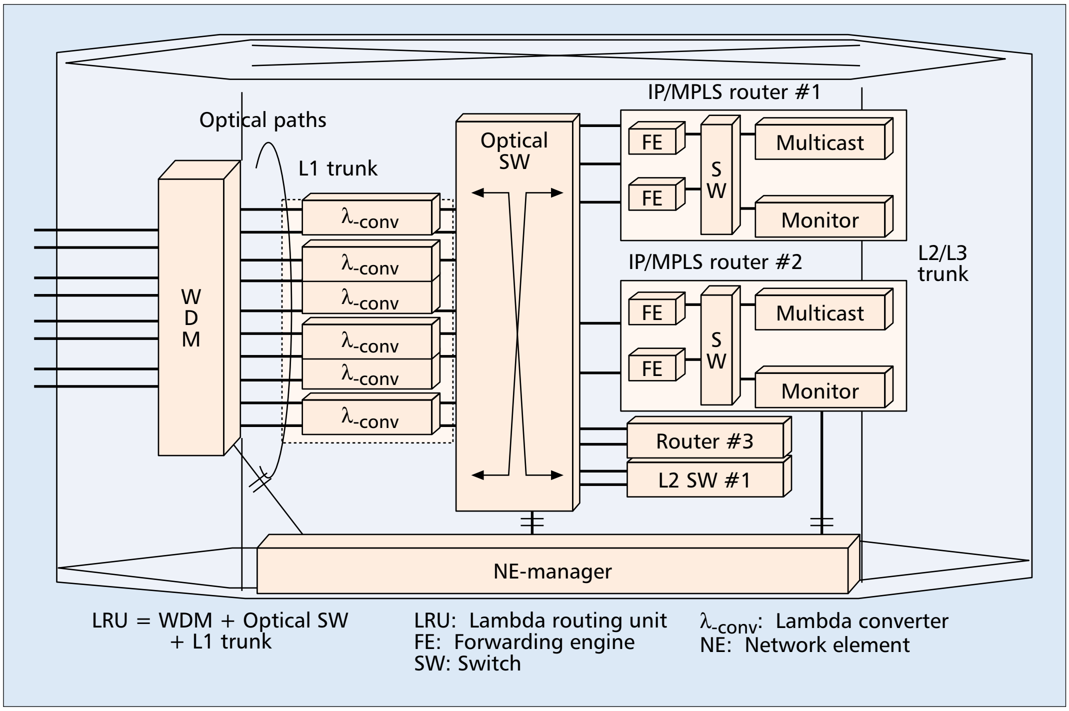

■ **Figure 1.** *The HIKARI router's functional configuration.*

The introduction of wavelength conversion can reduce the required wavelength resources by approximately 20 percent; however, it increases the node cost. A reduction in the number of wavelength converters and regenerators is required to realize cost-effective HIKARI router networks.

mapping between wavelengths and labels; therefore, the number of wavelength labels is limited because the state-of-the-art technology allows only a limited number of wavelengths.

The second modification is that an optical label switched path (OLSP) must be associated with a pair of conventional label switched paths (LSPs) because the OLSP is bidirectional and conversely, LSP is basically unidirectional. These differences severely affect the path control protocols. We implemented MPλS while taking into account these issues. This article reports on the concept of a photonic MPLS router (HIKARI router) and describes the usage of a kind of MPλS, which is implemented as a modified MPLS protocol.

This article also proposes a newly developed efficient disjoint path selection scheme with shared risk link group (SRLG) constraints, called a weighted SRLG (WSRLG) scheme. Finally, some demonstrations of HIKARI router networks are presented.

A Photonic MPLS Router (The HIKARI Router)

The Concept of the HIKARI Router

The HIKARI router incorporates not only lambda switching capability (LSC), but also packet switching capability (PSC) within one router box. Conventional intelligent optical crossconnect systems (OXCs) have only lambda switching capability or fiber switching capability (FSC). The conventional MPLS router has only the PSC function. The HIKARI router combines both LSC and PSC functions; thus, the advantages of both packet switching technology and circuit switching technology can be utilized with suitable router management systems.

The HIKARI routers establish IP networks over photonic networks with distributed autonomous control. By communicating with other routers, each HIKARI router controls the OLSP. According to the virtual wavelength path (VWP) concept [5], wavelength conversion is available in optical networks, and in the OLSP there is a wavelength label for each section. It is difficult to establish VWP networks; however, VWP achieves flexible selection of a label at each node in order to compensate for the small number of labels. The introduction of wavelength conversion can reduce the required wavelength resources by approximately 20 percent [5]; however, it increases the node cost. A reduction in the number of wavelength converters and regenerators is required to realize cost-effective HIKARI router networks. This topic is addressed in another paper [6].

The HIKARI router can handle both LSPs and OLSPs simultaneously because an LSP is handled by PSC and OLSP by LSC. LSPs are seamlessly connected by OLSPs, and LSPs are aggregated on OLSPs. Therefore, a controller can manage OLSPs as a layer in the LSP hierarchy. Deploying OLSPs improves the throughput of networks by taking advantage of the cut-through effect. HIKARI routers reduce the electrical forwarding fabric to approximately 1/3 or 1/2 in many cases [6]. This is one advantage of the switching capability combination.

As shown in Fig. 1, the HIKARI router comprises five functional blocks: a WDM function unit, an optical switch unit, an L1 trunk unit, an L2/L3 trunk unit, and a network element manager (NE manager). A lambda routing unit (LRU) is defined as an integrated unit comprising the WDM unit, the optical switch unit, and the L1 trunk unit. The LRU can switch and add/drop OLSPs, and wavelength conversion is performed

Items	Characteristics
Packet processing capability	Corresponds to max. 5 Gp/s (shared with L3 trunk and LRU)
System throughput	Max. 2.56 Tb/s
Interface for L3 trunk	Packet over SONET/SDH (POS), ATM, GbE, etc.
Interface between L3 trunk and LRU	POS (2.5 Gb/s or 10 Gb/s), 10 GbE-WAN PHY
Optical switches	Planer lightwave circuit thermo-optical. switches
Operating wavelength range	1550 nm band (C-band)
Optical channel speed	2.5 Gb/s or 10 Gb/s
Maximum number of wavelengths	32/fiber
Number of WDM fiber ports	Max. 8
Total switch scale	256 × 256 channels
Optical supervisory channel (OSC)	OC-3 (156 Mb/s) [9]
MPλS signaling channel	IP over ATM over OSC
MPλS protocol	Proprietary CR-LDP extension [9]

Table 1. *HIKARI router characteristics.*

at the λ-conv in L1 trunks. The HIKARI routers can exchange messages through the optical supervisory channel (OSC). The OSC and optical paths are multiplexed at WDM units. The NE manager monitors all the circuit elements in the node, supervises remote optical repeaters, performs restoration, monitors the quality levels of the signals (L1 level and L2 level), and controls the LSPs and OLSPs.

The proposed HIKARI router is based on a universal photonic platform or optical backplane with the addition of many trunks. L1 trunks can be replaced with λ-conv functions, signal regeneration functions (i.e., reshaping, retiming, and regeneration — 3R — functions), and optical amplifier functions. L2/L3 trunks can be replaced with IP router functions, MPLS router functions, and layer 2 switch functions. These functions are used adaptively. In other words, if a signal is degraded by fiber loss as well as nonlinear effects such as polarization mode dispersion (PMD) or amplified spontaneous emission (ASE), the 3R function is activated. In addition, wavelength conversion is also used when signaling is blocked by wavelength overbooking. Of course, L3 packet forwarding is used adaptively when L3 packet forwarding is performed.

Note that the HIKARI router can transfer three types of signals [6]. Type A involves L3 switching functions for operations such as MPLS path aggregation and L3 packet-level forwarding. This is the same as the conventional MPLS router signal flow. Type B represents relay connections that need wavelength conversion. Type B connections are also supported by the adaptive use of the 3R function. Finally, type C represents transparent transfer or bit-rate-restriction-free signals. The HIKARI router supports all transfer capabilities. Type C is not implemented in the prototype system described in this article.

HIKARI Router Characteristics

Table 1 gives the characteristics of the HIKARI router. The HIKARI router is an IP router system. Therefore, the packet processing capability is the most important. The developed HIKARI router system was designed to achieve correspondence to a maximum 5 gigapackets per second (5 Gp/s) capability. Some portion of the input packets are processed at L3 trunks on a packet switching basis, others at the LRU on a lambda switching basis.

We implemented an optical switch (planer lightwave circuit thermo-optics switch) based integrated OXC as the LRU. The LRU establishes both the optical path cross-connection and long-haul WDM transmission functionalities. Hence, this prototype system includes two optical network element (ONE) functions in one box. Most of the conventional OXCs require a WDM transmission system outside the OXC box. Contrarily, the LRU is equipped with the all-in-one type ONE. This feature aids in reducing operational costs, maintenance costs, device costs, office-space requirements, electrical energy, and the rate of failure. In the next generation, networks will be enormous, and these aforementioned features will provide great benefits.

The LRU has the maximum switching capacity of 256 × 256. Thus, 128 bidirectional optical paths can be accommodated. The optical path adaptation interfaces implemented in this system are synchronous optical network (SONET) OC-48c. Thus, the maximum total capacity is 640 Gb/s. If the interfaces are upgraded to OC-192c or 10 GbE, the capacity would become 2.56 Tb/s. Actually, the optical loss budget design was constructed to support 10 Gb/s optical path signals, making expansion possible without serious difficulties.

Optical Layer Management Characteristics

This section describes the operation, administration, and maintenance (OA&M) aspects regarding the optical layer of the HIKARI router. The implemented optical channel (OCh) frame format was a modified synchronous digital hierarchy (SDH) G.707 frame. This frame format will be changed to the OTN G.709 frame. The OSC carries the optical transmission section overhead (OTS OH), the optical multiplexing section overhead (OMS OH), and a high-speed data communication channel (DCC). The OSC was established by modification of the SONET OC-3 signal format. The overhead region of the OSC was rearranged for transmission in OTS and OMS OHs. The payload region of the OSC is used for DCC. OTS OH and OMS OH are used for WDM link management. The DCC is used for the network management channel and MPλS signaling channel. Data communication networks (DCN) that employ ATM are built based on DCC.

The NE manager controls and monitors

the corresponding hardware elements and enables communication among the other NEs (e.g., other HIKARI routers) in order to exchange MPλS signaling protocol messages via a modified CR-LDP and exchange OA&M messages. A preliminary console in the network operation center (NOC) was also developed. Operators can control and supervise remote NEs using the console. The Simple Network Management Protocol (SNMP) is used to manage HIKARI routers. The original LRU management information bases (MIBs) and OLSP MIBs were developed. About 50 MIBs were newly implemented to the NE manager.

Implementation of MPλS Signaling Protocol

The OLSP control plane of the HIKARI router is operated by CR-LDP extended for photonic network control. In the extended protocol, LSPs are handled as bidirectional paths for smooth connection with OLSPs defined as bidirectional paths, while conventional MPLS handles LSPs as unidirectional paths. This implementation of the protocol was developed with the fewest possible modifications. In fact, the same protocol core can be adapted to the standard and extended protocols. Some modifications have been implemented in the path connection point configuration and path termination point configuration. In standard CR-LDP, there is only one required connection in the NE (e.g., MPLS router) configuration for a unidirectional LSP. Contrarily, the extended CR-LDP must simultaneously handle a downstream connection and an upstream connection. The path connection/termination point configurations are performed consequently. When bidirectional path configurations are established in a distributed network management system, conflicts occasionally occur such as when two or more resource reservation requests are sent for the same resource at the same time. This conflict is avoided by using a priority control method implemented based on OLSP IDs. The signaling channel for CR-LDP is made with IP over ATM over OSC links. This IP network is also used as a data communication network (DCN) for network management. A network management system (NMS) can communicate with NEs via DCN using SNMP.

Photonic Network Protection Configuration

The HIKARI router provides many types of protection and restoration configuration utilizing the combination of 1+1, 1:1, restoration, or no protection on the photonic network side. In 1+1 protection both working and protection OLSPs are set between source and destination HIKARI router pairs. Traffic is bridged to both OLSPs.

On the other hand, in 1:1 protection, a protection OLSP can carry extra traffic. This extra traffic is not protected when the working OLSP experiences failure. In restoration, protection OLSPs are not actually set, rather the resources are reserved. These reserved resources can share with many working OLSPs; therefore, the required network resources can be reduced.

To realize protection and restoration functions, an efficient disjoint path selection algorithm and fast restoration signaling should be developed.

Disjoint Path Selection Algorithm

This section presents a proposal for an efficient disjoint path selection scheme with SRLG constraints called a weighted SRLG (WSRLG) scheme [7]. Disjoint path routing is used in protection path route calculation and restoration path calculation, described in the next section. Several disjoint paths, routed without sharing the same links or nodes, must be set between the OLSP source and destination HIKARI routers. This disjoint path calculation can be performed with SRLG advertisement. IP link-state-based routing protocols such as Open Shortest Path First (OSPF) and Intermediate System to Intermediate System (IS-IS) are being extended to support GMPLS by advertising traffic engineering (TE) link states. In the OSPF/IS-IS extensions, information pertaining to the SRLG is also advertised. For example, when multiple wavelengths are carried on the same fiber, the same SRLG value is assigned in this fiber segment. This means that when two paths have the same SRLG value in any segment, they share a common fiber and are not disjoint paths.

WSRLG treats the number of SRLG members related to a link as part of the link cost when the k-shortest path algorithm is executed. In WSRLG, a link that has many SRLG members is rarely selected as the shortest path.

A k-shortest path algorithm [8] is widely used to find disjoint paths because of its simplicity; we first explain the problem that disjoint paths cannot be found effectively with SRLG constraints. Figure 2a shows a network example. Consider the solution of disjoint paths between source node 0 and destination node 6. Link cost $C_{OSPF}(i, j)$ for link $L(i, j)$ is advertised by the OSPF routing protocol.

$srlg(i, j, g)$ indicates the SRLG information, where $srlg(i, j, g) = 1$ or 0 means that $L(i, j)$ does or does not belong to SRLG g, respectively. $L(5, 6)$ and $L(2, 6)$ belong to SRLG 0. When the k-shortest algorithm is used by taking C_{OSPF} as the link cost, route 0-1-2-6 is selected as the shortest path. To find the second disjoint path, links and nodes on the first selected path, which are $L(0, 1)$, node 1, $L(1, 2)$, node 2, and $L(2, 6)$, are pruned. In addition, since $L(5, 6)$ belongs to SRLG 0, to which $L(2, 6)$ belongs, $L(5, 6)$ is also pruned. As a result, we cannot find more than one disjoint path between nodes 0 and 6, as shown in Fig. 2b, although there are two possible disjoint paths in the given network.

To overcome this problem, the WSRLG scheme is employed to find disjoint paths in the Constraint-Based Shortest Path First (CSPF) engine.

In WSRLG, $C_{comp}(i, j)$ is considered the link cost for $L(i, j)$ used to find k-shortest paths, instead of $C_{OSPF}(i, j)$. $C_{comp}(i, j)$ is defined by

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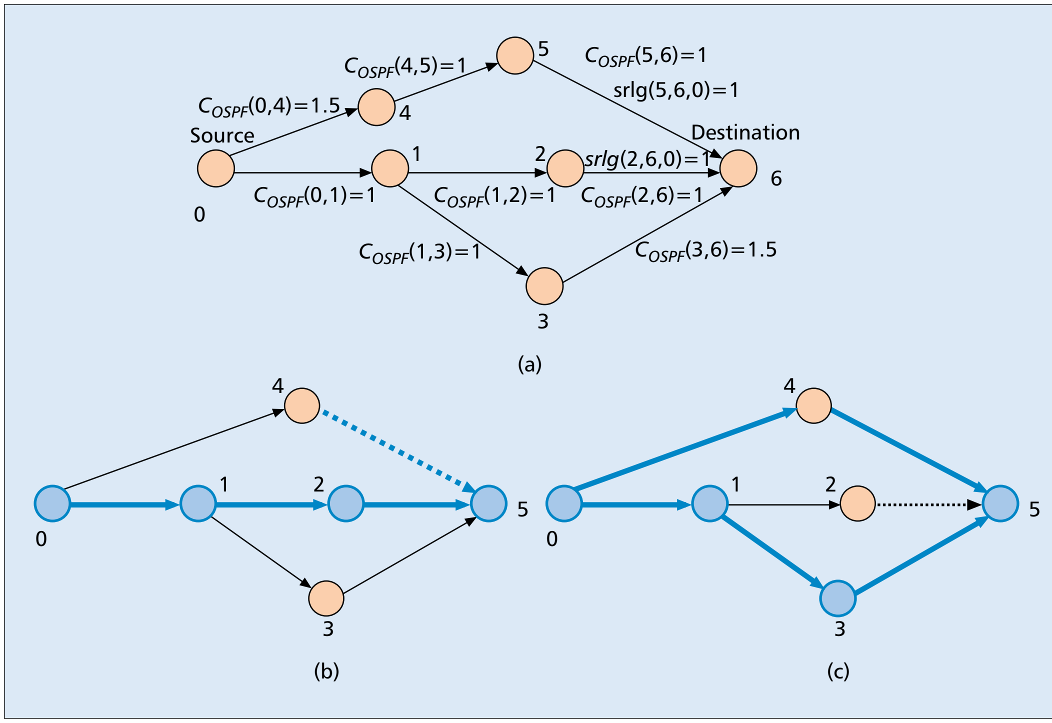


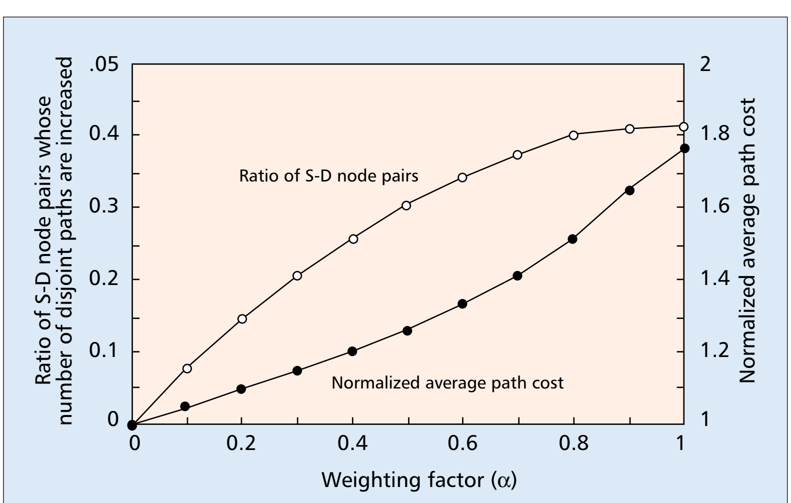
■ **Figure 2.** *Disjoint path selection with SRLG constraints: a) network example; b) conventional algorithm; c) WSRLG algorithm.*

$$C_{comp}(i,j)=\frac{1-\alpha}{C_{OSPF}^{\max}}C_{OSPF}(i,j)+\frac{\alpha}{SRLG^{\max}}\max\{SRLG(i,j),1\}, \tag{1}$$

where

$$SRLG(i,j)=\sum_{g}^{G}M(g)srlg(i,j,g), \tag{2}$$

$$C_{OSPF}^{\max}=\max_{i,j}C_{OSPF}(i,j), \tag{3}$$



■ **Figure 3.** α *vs. ratio of S-D node pairs whose number of disjoint paths is increased and path cost* $D_{path}(s,d)$. *(N = 20, D = 6, G = 16, m = 14.)*

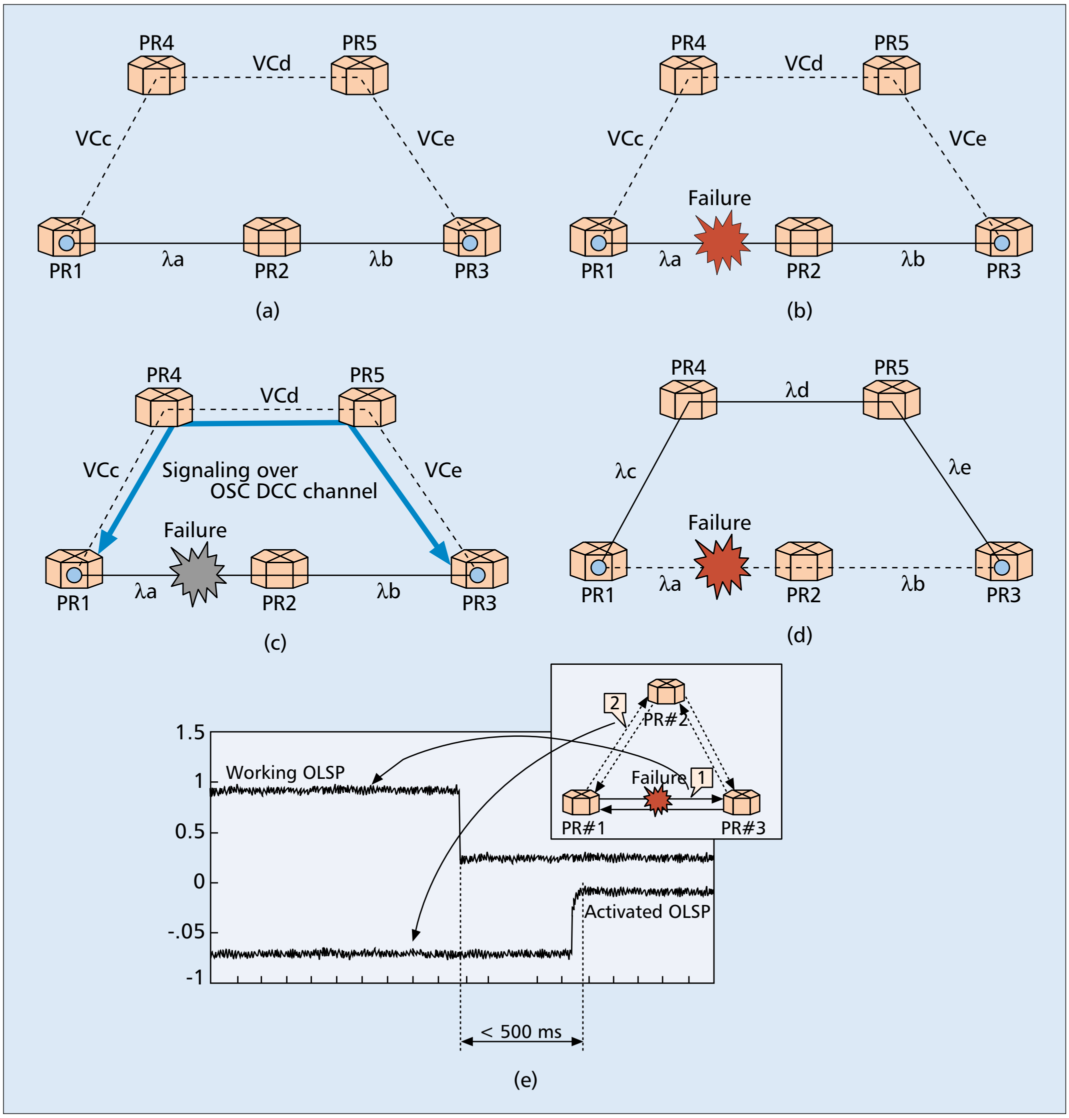
and

$$SRLG^{\max}=\max_{i,j}SRLG(i,j). \tag{4}$$

Here, α is a weight factor for SRLG. $M(g)$ $(=\Sigma_i \Sigma_j\, srlg(i,j,g))$ is the number of members for SRLG, g. In WSRLG, α is set to the smallest value possible by using a well-known binary search method under the condition that the obtained number of disjoint paths is equal to or greater than the required number [7]. As α increases, the average number of disjoint paths becomes large, and the average path cost becomes large, but it should not become larger than the original OSPF path cost. Therefore, the optimum value search of α is important. In WSRLG, the optimum α value can be automatically determined.

Consider a WSRLG applied to the network model in Fig. 2a. α is set to 1.0, as a special case. WSRLG finds two disjoint paths between nodes 0 and 6, while the conventional k-shortest scheme finds only one path. C_{comp} (2, 6) and C_{comp} (5, 6) are twice as large as other $C_{comp}(i, j)$. Route 0-1-3-6 is selected as the shortest path. Then route 0-4-5-6 is found as the second shortest path, as shown in Fig. 2c. Thus, WSRLG is able to find more disjoint paths.

To evaluate WSRLG performance, we use network topologies generated in a random manner under the condition that average node degree $D = 6$ is satisfied for a given number of nodes $N = 20$, and at least one path exists between every source-destination node pair. D is the average number of other nodes to which individual nodes are connected by links. $M(g)$ is set to $m = 14$, which is independent of g, to simplify the discussion. $srlg(i, j, g)$ is set randomly



■ **Figure 4.** *Fast restoration procedure: a) restoration configuration; b) link failure; c) signaling for restoration path configuration; d) restoration completion; e) experimental results of restoration demonstration. PR: photonic MPLS router, VCx: virtual channel on DCN; λ_x: OLSP with wavelength x.*

The optimum value of α is varied with the source and destination pairs. By using WSRLG, α is automatically determined so that the required number of disjoint paths can be found while suppressing the increase in path cost.

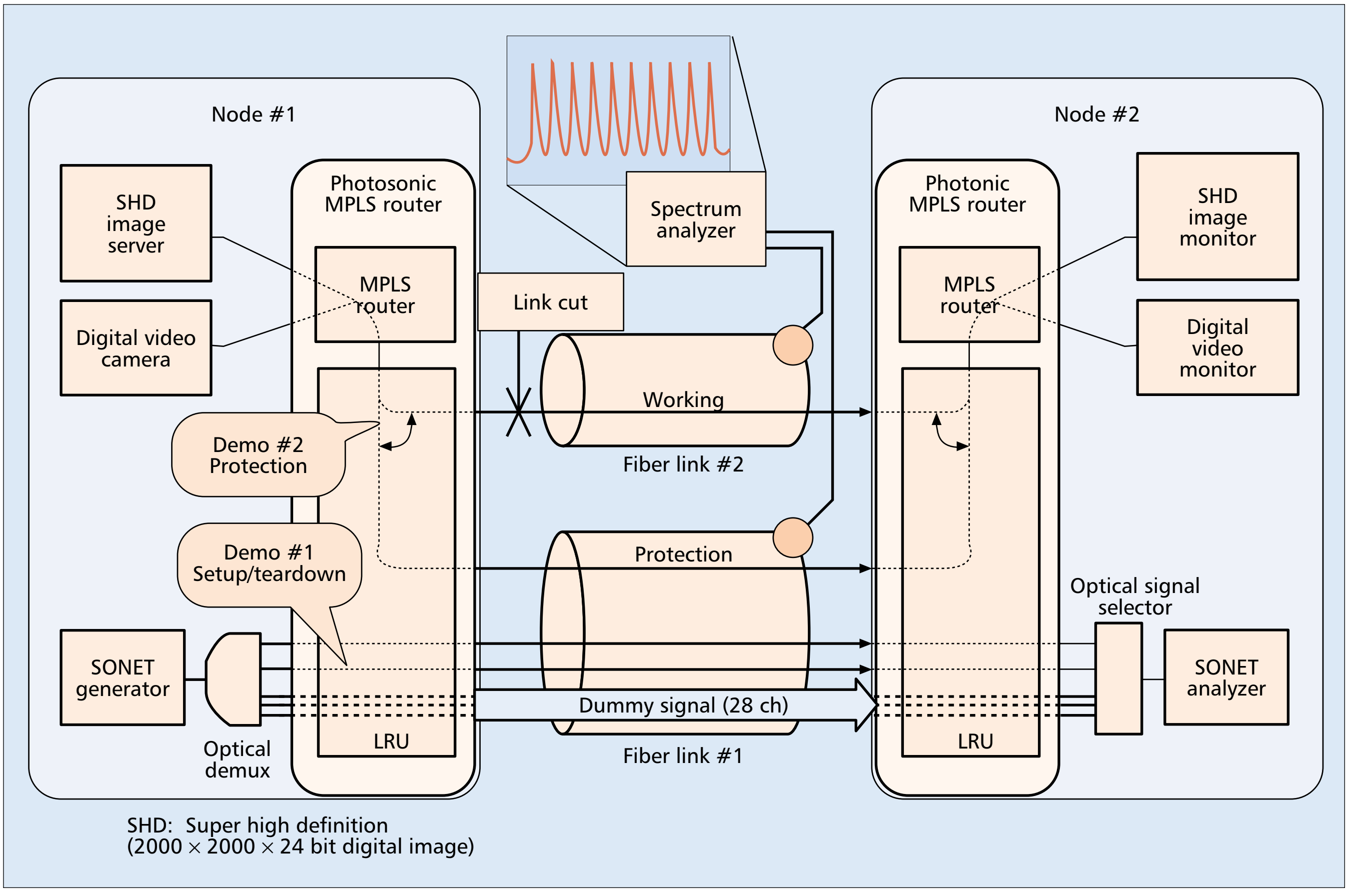
under the condition that $\Sigma_i \Sigma_j srlg(i, j, g) = m$ is satisfied. C_{OSPF} is set randomly between 0 and 1. G is set to 16. The number of sample network topologies for each evaluation is more than 100.

Figure 3 shows how many source-destination node pairs have more disjoint paths for $\alpha > 0$ than for $\alpha = 0$, divided by the total number of source-destination node pairs, expressed as a ratio. Figure 3 also shows the normalized average path cost of $C_{path}(i, j)$, where the path cost for $\alpha = 0.0$ is assumed to be 1.0. $C_{path}(s, d)$, which is defined as $\Sigma_{k=1}^{K} \Sigma_{(i,j) \in \text{path}k}\, C_{OSPF}(i, j)$, is the sum of costs for all disjoint paths between nodes s and d. In our evaluation, we set α manually to show its dependency. As α increases, the ratio of source-destination router pairs whose number of disjoint paths is increased becomes large. When $\alpha = 1$, the ratio is 41 percent higher than that for the conventional algorithm. Note that $\alpha = 0$ means that the conventional disjoint path selection algorithm is used. The normalized average path cost also increases with α. When α is large, the second term in Eq. 1 is taken into account more than the first term in finding the shortest paths. The optimum value of α is varied with the source and destination pairs. By using WSRLG, α is automatically determined, so the required number of disjoint paths can be found while suppressing the increase in path cost. More detailed performance evaluation results of WSRLG are presented in [7].

PROTECTION AND RESTORATION FUNCTIONS

This section presents the implemented protection and restoration functions [9, 10].

Automatic protection switching (APS)-based protection (1+1 and 1:1) was implemented in the HIKARI router (photonic MPLS router, PR). Less than 20 ms protection time was achieved. A new fast restoration scheme was also implemented on the HIKARI routers. Figure 4 shows the restoration procedures. The sample configuration is shown in Fig. 4a. An OLSP is established between PR1 and PR3 via PR2, and λ_a was assigned to the link between PR1 and PR2, while λ_b was assigned to the link



■ **Figure 5.** *Configuration of the photonic MPLS router demonstration at SUPERCOMM 2001.*

between PR2 and PR3. On the other hand, the restoration path is calculated before any fault occurs, and the resources are reserved in the new method. Reservation for the restoration path corresponding to the OLSP is performed on a DCN over OSC DCC channels. As mentioned in an earlier section, the OSC carries ATM traffic. Some ATM virtual circuits (VCs) are set as reserved on the OSC. In this case, the VCs are allocated to three sections: PR1-PR4, PR4-PR5, and PR5-PR3. When a failure occurs in the link between PR1 and PR2 (Fig. 4b), optical path setup signaling is transported to related PRs through the VCs over OSC (Fig. 4c). The restoration path is established on the same route after signaling is successfully completed. All the nodes are connected to new optical paths according to the VC identifiers on the route of the restoration path. The mapping scheme is such that VC_a is mapped to λ_a and so on. Therefore, the wavelength assignments are simultaneously completed (Fig. 4d). The detailed experimental results of the developed restoration scheme are described in a later section.

Demonstration of the HIKARI Router

The functions of the developed HIKARI routers were demonstrated at SUPERCOMM2001 (June 2001) [9]. OLSP setup/teardown and OLSP protection were successfully performed. Figure 5 shows the configuration of the demonstration. As mentioned in an earlier section, less than 20 ms OLSP protection time was achieved. For the digital video stream demonstration (demo #2), 20 ms is sufficient to prevent video stream frame misalignment. Another demonstration conducted was the automatic OLSP setup/teardown procedure (demo #1). An operator initiated the OLSP setup command to PR#1 via the NOC console. PR#1 determined the OLSP route according to the command. PR#1 first sent a Label Request message to PR#2. PR#2 received the message and replied by sending a Label Mapping message back to PR#1. After this signaling process, the OLSP was successfully established in less than 1 s. In this demonstration, OLSP setup/teardown was repeated in a 5 s cycle time.

Next, we examined the restoration function. A triangle network was constructed with three PRs (Fig. 4e). A working path was established between PR#1 and PR#3. A restoration path was reserved between PR#1 and PR#3 via PR#2. The working path was intentionally cut. PR#3 detected signal failures as restoration triggers in the path termination points (TPs). Then PR#3 initiated a restoration request to the other end of the corresponding path. Figure 4e shows the preliminary results of the demonstration. In the figure, the number in the balloons represents the measuring point. Measuring point 1 was set on the working path between PR#1 and PR#3. Measuring point 2 was set on the route of the restoration path. The restoration procedures were completed within 500 ms. The service down time in the SONET layer was evaluated and was approximately 650 ms. The service down time in the PPP layer was evaluated and was approximately 700 ms. The restoration time was sufficiently short to restore IP over photonic networks without initiating any recovery mechanism on the IP layer.

CONCLUSION

A new photonic MPLS router (HIKARI router) was developed to integrate IP/MPLS router functions and MPλS switching function. The demonstration system achieved a distributed autonomous system through an extended CR-LDP protocol and conventional layer 3 routing protocols, and fast self-healing through automatic protection switching and a new restoration scheme. These functions were successfully implemented, and the performance was verified on a demonstration network. A fast restoration scheme was also verified. The scheme is a type of preassignment method. A backup route can be calculated using the proposed disjoint path selection algorithm. The restoration scheme was implemented on HIKARI routers and tested on a triangle network.

The restoration time was less than 500 ms in the optical domain, approximately 650 ms in the SONET layer, and approximately 700 ms in the PPP layer. The performance is sufficiently quick for fast recovery in IP over photonic networks. We successfully demonstrated highly reliable photonic MPLS networks.

The demonstration system achieved a distributed autonomous system through an extended CR-LDP protocol and conventional Layer-3 routing protocols, and fast self-healing through automatic protection switching and a new restoration scheme.

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