Multilayer Networking Architecture for Heterogeneous Service Provisioning

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List of publications

Journal papers

[1] J. Murayama and T. Kubo, "Hybrid Access Control for Broadcast-based ATM-LAN," IEICE Transactions on Communications, Vol.E78-B, No.4, pp.523-530, April 1995.

[2] J. Murayama, H. Kitazume, N. Kukutsu and H. Hara, "Cell-Attached Frame Encapsulation Schemes for a Global Networking Service Platform," IEICE Transactions on Communications, Vol.E80-B, pp.1429-1435, No.10, October 1997.

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Abstract

This thesis proposes a multilayer networking architecture for a large-scale data communication network to provide a wide spectrum of communication services using the optical path technology. Communication networks have been ubiquitously utilized for the different types of purposes and thus service requirements for those networks have been diversifying. However, most conventional communication networks have been designed for supporting only a specific service.

The proposed architecture can satisfy the requirements of heterogeneous service provisioning by way of a network hybridization approach. In this design, the multilayer data forwarding technology, the multi-priority path allocation technology and the multi-policy path routing technology are proposed to solve the three fundamental problems of network hybridization as follows:

The first problem is how to hybridize multiple transfer networks with each other in order to compose a single service network. This is essentially a problem of transfer network selection. For solving this problem, the multilayer data forwarding technology is proposed. In this technology, an optical path network and an electrical connectionless network are hybridized with each other and they compose a best-effort service network. Because of the appropriate transfer network selection according to traffic patterns, throughput of the whole network can be increased effectively. In order to achieve this control rapidly against frequently fluctuated traffic patterns and routing information, overlay networking and electrical cut-through control are further deployed in this technology. The results of the mathematical analysis have shown that the number of required optical paths in the network can be adjusted according to traffic demand because of the optical cut-through control. In addition, due to the overlay networking, the number of optical path signaling routes to be handled by each core router can be reduced to be the same as that of edge routers in the network. Furthermore, owing to the electrical cut-through control, the number of packet forwarding routes to be handled by each edge router can be reduced to be the same as that of accommodated customers by that router. On the other hand, in the peer-based basic approach, both numbers become almost the same as that of the Internet full routes.

The second problem is how to hybridize a best-effort service network with a bandwidth-reserved service network over a single provider network. This can be abstracted as a problem of bandwidth resource utilization. As the solution of this problem, the multi-priority path allocation technology is proposed. In this technology, optical paths for the best-effort service are first allocated as much as possible. Specifically, optical paths for the bandwidth-reserved service are then allocated as demanded. In order to allocate a sufficient number of bandwidth-reserved service paths, best-effort

service paths that interfere with bandwidth-reserved service paths are released and the rest of traffic to be carried using the released paths is carried by means of the electrical connectionless network. The results of the experiments using prototype systems have indicated that those two service networks can be combined with each other over the single provider network and they can control an optical path dynamically, with a response time of the order of ten seconds. Consequently, this loss-based path allocation scheduling achieves bandwidth resource sharing between those two service networks and throughput of the whole network can be increased efficiently.

The third problem is how to hybridize the differentiated bandwidth-reserved service networks with each other over a single provider network. This can be formalized as a problem of multi-service provisioning. In order to solve this problem, the multi-policy path routing technology is proposed. In this technology, in order to offer the differentiated services, the optical path network is first partitioned logically and the different routing algorithms are applied to these partitions. They are then integrated into the single optical path network and the interfered paths are arbitrated by means of the delay-based path allocation scheduling because those paths cannot be released until the communications using the path have been completed. In the results of the computer simulations, the latency of the minimum-hop routed paths was decreased to be almost half of that of the minimum-interference routed paths. In addition, the throughput of the high-priority paths was increased in the maximum by about forty percent, while that of low-priority paths was decreased in the maximum by about forty percent. Accordingly, this technology achieves service differentiation and bandwidth resource sharing even between bandwidth-reserved service networks.

Since those technologies cover basic patterns of network hybridization, the proposed architecture is suitable for the data communication service infrastructure to provision heterogeneous services.

Chapter 1

Introduction

1.1 Thesis goal

The thesis goal is to establish a multilayer networking architecture for service providers to provision heterogeneous services according to the following backgrounds: Data communication networks such as the Internet have been enlarging[1] and their traffic amount has been increasing[2]. In addition, most customers have come to use diverse applications for achieving ubiquitous communications. These applications require diverse data transfer services. For simple example, file transfer[3], telephone[4] and e-mail[5] prefer high-throughput, low-latency and low-cost data transfer, respectively. Furthermore, diverse customers require the different types of services. For typical example, enterprise customers and personal customers tend to demand reliable services and economical services, respectively. Although service requirements have been diversifying, most conventional networks have been designed for a specific service. Moreover, they have come to be integrated into some large-scale networks because of economical and convenient service provisioning. Therefore, it has become an important problem for hybridized service networks to improve throughput of the whole network from the viewpoint of service providers.

1.2 Open problems

Multilayer networks are attractive as the platform for heterogeneous service provisioning. However, following three open problems should be solved:

(1) Transfer network selection

How to select an appropriate transfer network from the different types of networks is a basic problem for improving throughput of the whole network efficiently. In order to achieve broadband communication, the optical path networking technology[6] seems attractive. However, in actual, this technology is only effective for carrying a large amount of traffic towards a specific destination. In order to carry a small amount of traffic towards many destinations, the electrical connectionless networking technology[7] is still effective. Consequently, appropriate network selection according to traffic demands is a key to improving throughput of the whole network, while it is not necessarily easy because traffic patterns may fluctuate frequently.

In order to optimize path allocation patterns, optical paths are allocated according to the flow amount as shown in Fig.1.1(A). Here, a flow means a kind of traffic that carried between a specific pair of edge routers. Since reachability is maintained using the electrical network, flows are initially carried via this network and their amounts are measured. When the amount of a specific flow becomes more than the threshold of path allocation, the new optical path is allocated for that flow. This path is released if its flow amount becomes less than the threshold of path release. The repetition of those procedures optimizes path allocation patterns and thus throughput of the whole network is improved.

In this approach, optical paths and electrical routes should be reallocated frequently according to fluctuations in traffic patterns and routing information. Thus, lightweight processing is important for both optical path control and electrical route control. One of the promising approaches for this issue is to simplify the configuration of the optical network by utilizing the overlay networking technologies as shown in Fig.1.1(B). Such rapid control is important to maintain throughput against frequently fluctuated traffic patterns.

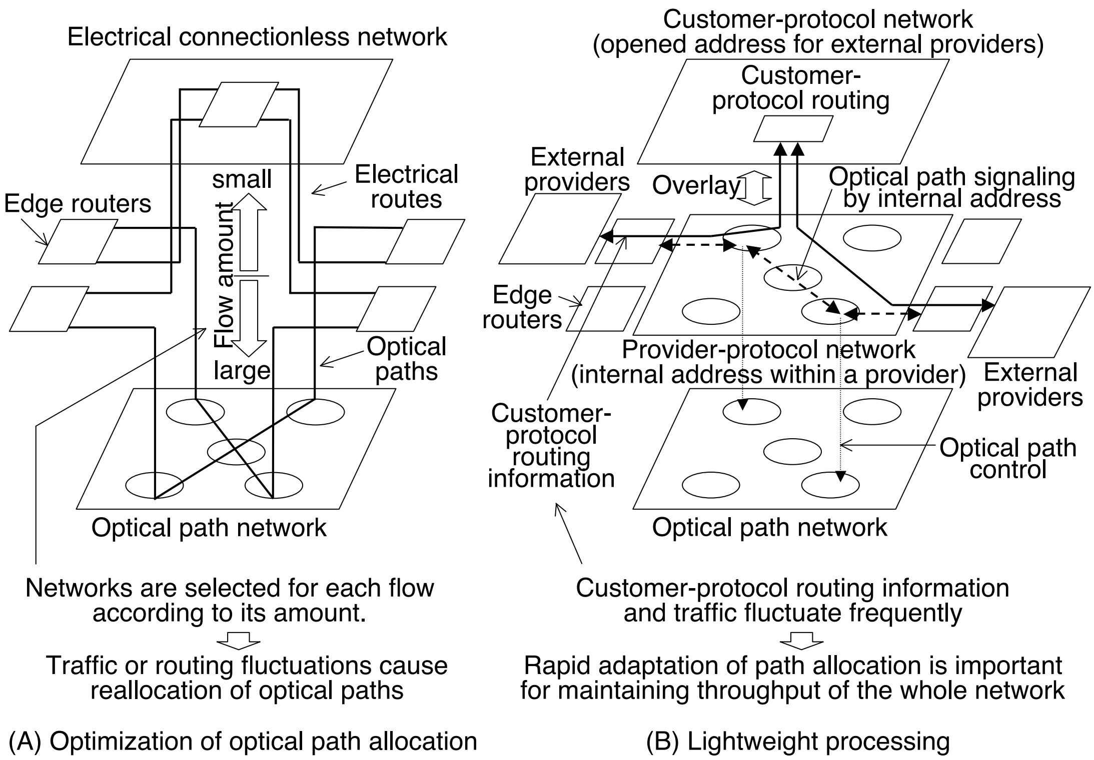

Figure 1.1: Transfer network selection

(2) Bandwidth resource utilization

How to integrate the different types of service networks into a single transfer network is a key problem for efficient bandwidth resource utilization.

In the bandwidth resource dedication approach shown in Fig.1.2(A), a transfer network is physically partitioned and each service dedicates its own physical partition. Since bandwidth resources cannot be shared between physical partitions, each throughput is stabilized. However, bandwidth loss may be incurred.

On the other hand, in the bandwidth resource sharing approach shown in Fig.1.2(B), a transfer network is partitioned logically and bandwidth resources can be shared between services. Thus, throughput of the whole network can be improved without additional bandwidth resources. However, contention arbitration of bandwidth resources is required additionally.

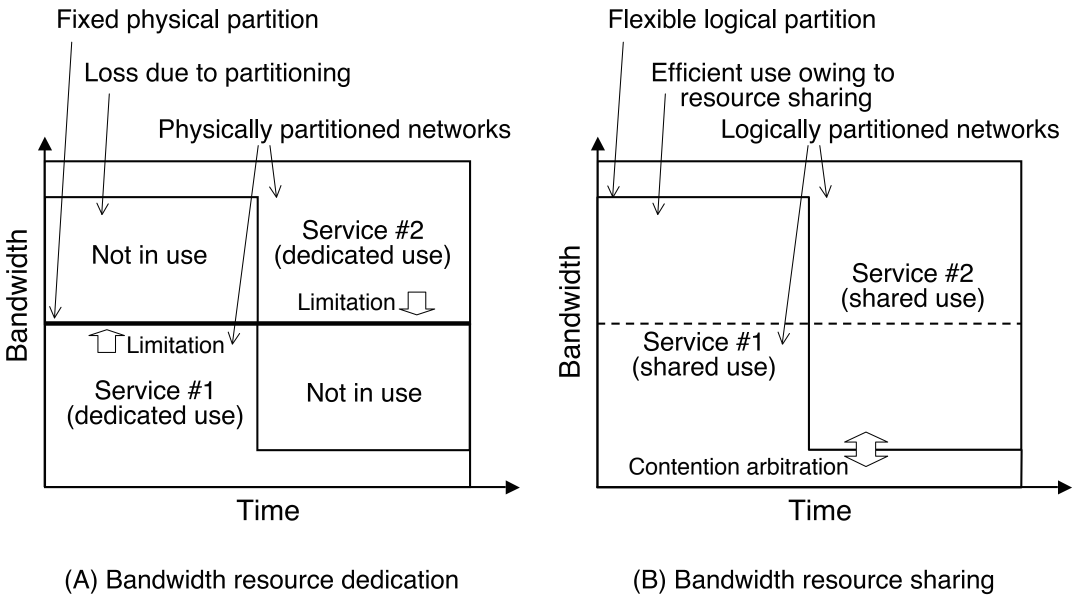

Figure 1.2: Bandwidth resource utilization

(3) Multi-service provisioning

How to differentiate service characteristics between component networks is an essential problem for provisioning wide variety of services.

In the homogeneous service provisioning approach shown in Fig.1.3(A), many virtual private networks (VPNs) can be generated and offered to customers. Although VPNs are logically isolated, they share the same transfer network with each other and thus their service characteristics become similar to each other.

On the other hand, in the heterogeneous service provisioning approach shown in Fig.1.3(B), a transfer network is partitioned into several partitions logically. Thus, service differentiation can be achieved by means of the different configurations of the partitions. However, bandwidth resource sharing between those partitions is required additionally.

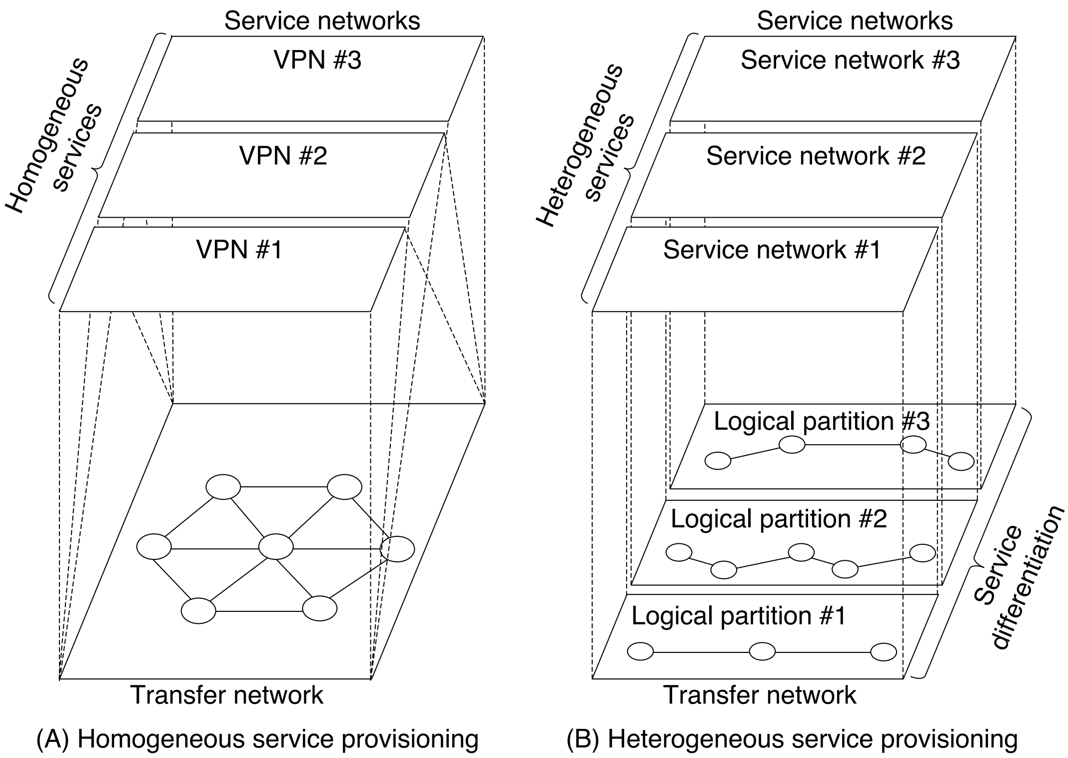

Figure 1.3: Multi-service provisioning

1.3 Proposed solutions

In order to solve the three open problems, this thesis proposes a multilayer networking architecture depicted in Fig.1.4. This architecture is designed based on the following three solutions for the open problems:

(1) Multilayer data forwarding

The multilayer data forwarding technology[8] is designed for a large-scale network to efficiently provide a best-effort data forwarding service. This technology solves the problem of transfer network selection for optimizing optical path allocation as follows: First, optical paths are allocated as much as possible. Then, flow amount is compared between electrical flows and optical flows. When the largest electrical flow amount becomes more than the smallest optical flow amount, the corresponding optical path is replaced with the new path established for the electrical flow. This approach is effective in improving throughput of the whole network and in reducing path replacing frequency.

In addition, the designed technology also achieves lightweight processing for transfer network selection according to the combined approaches of overlay networking and electrical cut-through control. In the overlay networking approach, a provider-protocol address can be separated and closed from a customer-protocol address. Thus, optical path signaling can be achieved using only the closed provider-protocol address. Although the routing information for interconnecting external provider networks fluctuates frequently, this approach is effective in reducing the amount and fluctuation frequency of the routing information required for optical path signaling. In the electrical cut-through control approach, the customer-protocol routing information is used centrally by the customer-protocol core router and thus customer-protocol forwarding information is notified only as needed to the edge routers that terminate optical paths. This approach is effective in reducing the amount and fluctuation frequency of forwarding information using optical paths.

The combination of all those approaches can reduce frequency of optical path replacements and processing load of each replacement. Consequently, this technology basically improves throughput of the whole network by using all the available optical path resources and additionally maintains the throughput against the frequently fluctuated customer-protocol routing information and traffic patterns. This technology is verified by means of the mathematical analysis from the viewpoint of scalability and stability.

(2) Multi-priority path allocation

The multi-priority path allocation technology[9] is designed to offer a bandwidth-reserved data forwarding service and a best-effort data forwarding service simultaneously. In order to improve the total throughput of these services, this technology solves the problem of bandwidth resource utilization by way of the bandwidth resource sharing approach.

In this technology, optical paths for the best-effort service are first allocated as much as possible. Specifically, optical paths for the bandwidth-reserved service are then allocated as required. Best-effort service paths that interfere with bandwidth-reserved service paths are released and the rest of traffic to be carried using the released paths is carried by the electrical network. This loss-based path allocation scheduling is effective to improve the total throughput of the bandwidth-reserved service without excessive throughput degradation of the best-effort service.

Accordingly, this technology hybridizes a best-effort service network with a bandwidth-reserved service network so as to share their bandwidth resources and to increase the total throughput of those services. Feasibility of this technology is verified by means of the experiments using prototype systems.

(3) Multi-policy path routing

The multi-policy path routing technology[10] is designed to satisfy differentiated policies according to service demands. This technology solves the problem of multi-service provisioning by way of the heterogeneous service provisioning approach. This approach is further combined with delay-based path allocation scheduling so as to improve the total throughput of those heterogeneous service networks.

In this technology, an optical service provider network is partitioned logically into multiple component networks and their characteristics are differentiated by applying the different types of routing algorithms. Moreover, delay-based path allocation scheduling is deployed to achieve bandwidth resource sharing even between bandwidth-reserved services where an optical path cannot be released in the middle of the communication.

For practical example, a best-effort service network, a fair-latency bandwidth-reserved service network and a low-latency bandwidth-reserved service network are provisioned using the minimum-interference routing algorithm, the widest-shortest path routing algorithm and the minimum-hop routing algorithm, respectively. In addition, as the loss-based path allocation scheduling, high priority and low priority are assigned to the bandwidth-reserved services and the best-effort service, respectively. Furthermore, as the delay-based path allocation scheduling, high priority and low priority are assigned to the low-latency service and the fair-latency service, respectively.

Therefore, this technology satisfies wide range of service requirements and also improves throughput of the whole network. Effect of this technology for service differentiation is verified by means of the computer simulations.

Those three technologies cover fundamental network hybridization patterns and thus the proposed multilayer networking architecture achieves wide applicability for offering heterogeneous communication services. Furthermore, this architecture enables hybridized service networks to improve throughput of the whole network.

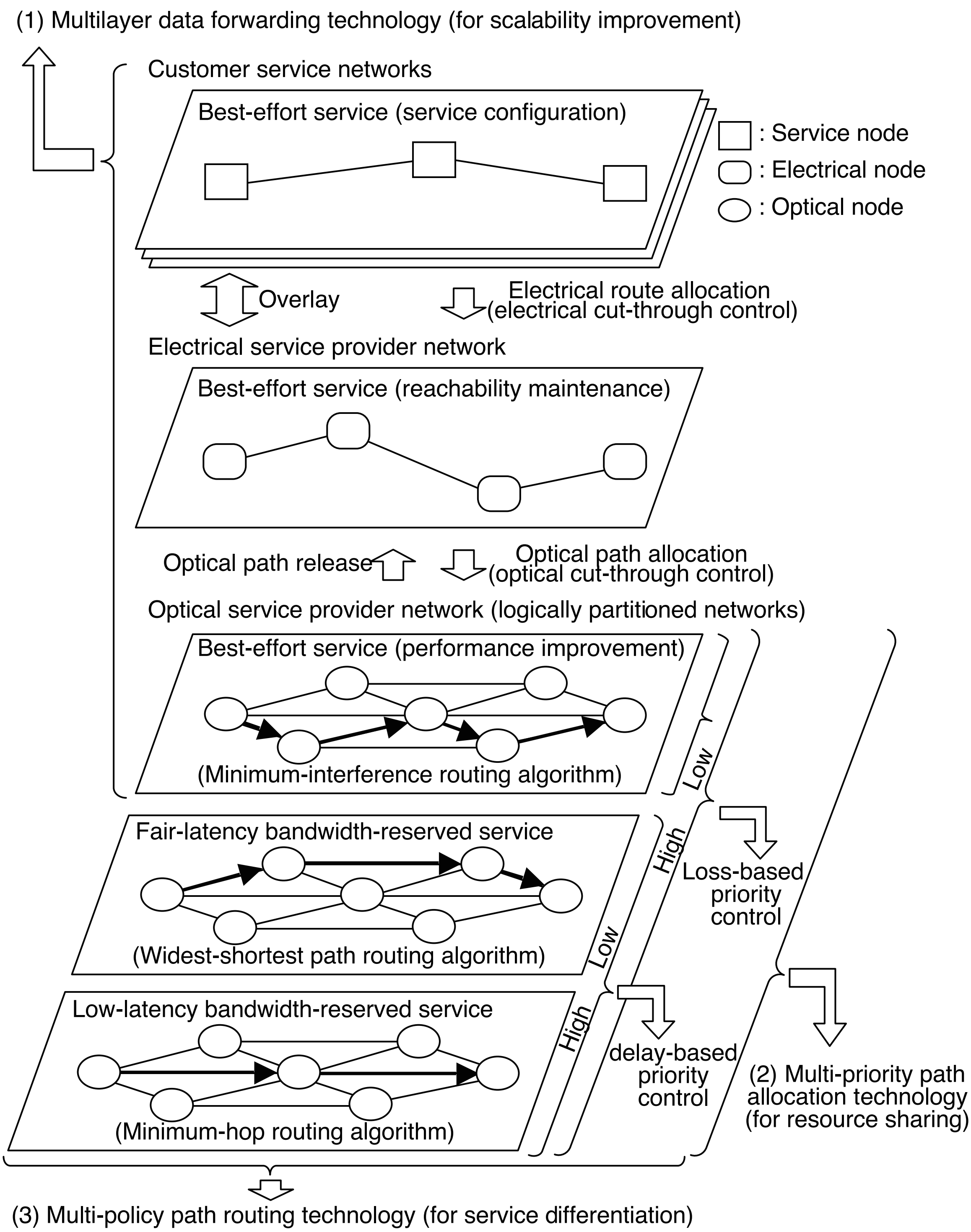

Figure 1.4: Multilayer networking architecture

1.4 Thesis organization

The organization of this thesis is as follows:

- Chapter 1 introduces this thesis and proposes the multilayer networking architecture. The thesis goal, open problems and the proposed solutions are summarized in this chapter.
- Chapter 2 proposes the multilayer data forwarding technology. The reference network model, the related technologies, the proposed data forwarding technology and its evaluation results are described in this chapter.
- Chapter 3 proposes the multi-priority path allocation technology. The reference network model, the related technologies, the proposed path allocation technology and its evaluation results are shown in this chapter.
- Chapter 4 proposes the multi-policy path routing technology. The reference network model, the related technologies, the proposed path routing technology and its evaluation results are stated in this chapter.
- Chapter 5 concludes this thesis with providing brief summaries and future works.

Chapter 2

Multi-layer data forwarding

In this chapter, a multilayer data forwarding technology is proposed. This technology is designed to provision a best-effort data forwarding service effectively. Its design is derived from the connectionless network emulation technology using optical paths, which provides high performance but is not scalable since both optical paths and electrical packet forwarding routes need to be arranged in a mesh topology. To improve scalability, the configuration is first modified so that optical paths and electrical routes can be arranged in a tree topology. However, this approach may degrade performance due to traffic concentration at each tree's root. To prevent such performance degradation, the proposed technology is further modified so that both cut-through optical paths and cut-through electrical routes can be allocated reactively, according to traffic demand, and these can work together in cooperation. This provider network is concealed from other provider networks by means of an overlay networking approach and thus lightweight processing for optical path allocation is also achieved. According to the results of the mathematical analysis, the proposed technology achieves both high performance and scalability, in that the whole network performance can be maintained without a massive increase in the number of optical paths and electrical routes, even if the number of customer networks grows.

2.1 Introduction

Best-effort data forwarding services by means of the electrical packet forwarding technology have spread widely and the ensuing traffic has increased explosively. To handle such traffic, network throughput and scalability need to be improved. Here, network throughput means the total throughput of the whole network. On the other hand, network scalability reflects how many edge routers that accommodate customers can be connected to the network.

A promising technology to improve network throughput is to replace electrical packet forwarding[7] by optical path cross-connection[6]. In this technology, an optical path cross-connect (OXC)[11] deploys its controller that performs optical path routing and signaling[12] in order to establish an optical path. A broadband feature of the optical path is attractive to achieve high network throughput.

However, this solution does not improve network scalability, because a "connection-oriented" optical path network cannot accommodate a large number of edge routers when it simply emulates a "connectionless" packet forwarding network. In the optical path network, in order to ensure full "reachability" of all edge routers, optical paths need to be arranged in a mesh topology, regardless of the optical traffic demand on each. This may cause a massive increase in the number of optical paths. Furthermore, edge routers are forced to support a large number of electrical packet forwarding routes.

In order to achieve both high network throughput and large network scalability in both optical and electrical layers, in this chapter, a multilayer data forwarding technology is proposed. This technology is based on the connectionless network emulation technology using optical paths, but it is first modified so that optical paths and electrical packet forwarding routes can be arranged in a tree topology. Then, it is further modified so that both cut-through optical paths and cut-through electrical routes can be allocated reactively, according to traffic demand, and in such a way that they can work together in cooperation.

In this technology, optical paths are allocated as much as possible to utilize the whole supplied path resources. Then, flow amount is compared between electrical flows and optical flows. When the largest electrical flow amount becomes more than the smallest optical flow amount, the corresponding optical path is replaced with the new path established for that electrical flow. Thus, congestion is prevented proactively. In addition, the optical provider network is concealed from external service provider networks by means of an overlay networking approach and finally lightweight processing for optical path allocation is also achieved.

The results of mathematical analysis have shown that the proposed technology achieves both high throughput and scalability, in that the whole network throughput can be maintained without a massive increase in the number of optical paths and electrical routes, even if the number of customer networks grows.

In this chapter, the reference network model is shown in Section 2.2 and the related technologies are summarized in Section 2.3. Then, the proposed technology is described in Section 2.4 and its scalability is evaluated in Section 2.5. Finally, a brief conclusion is provided in Section 2.6.

2.2 Reference network model

The reference network model used to study the multilayer data forwarding technology is shown in Fig.2.1. This model is based on the provider-provisioned virtual private network (PPVPN) framework[13] that describes a large-scale network in general terms. This model comprises a service provider (SP) network, access networks and customer networks.

An SP network comprises provider core (PC) routers and provider edge (PE) routers. The role of this SP network is to carry traffic between PE routers as a backbone network. A PC router comprises an optical path cross-connect (OXC) and its controller (CTL)[12]. On the other hand, a PE router comprises electrical data forwarder and its CTL. PC and PE routers are connected to each other by means of optical fiber links using the Dense Wavelength-Division Multiplexing (DWDM) technology[14].

An access network comprises a PE router, access router and customer edge (CE) routers. The role of this access network is to physically aggregates customer-side access lines into a provider-side access line and provides access connections logically between a PE and CE routers.

A customer network is an end-user network composed of a CE and customer routers. Another SP network may be connected to a PE router instead of a customer network.

An SP network provides optical paths between a pair of PE routers according to a following three-step procedure: First, the customer-protocol routing information is exchanged between neighboring CTLs using a customer routing protocol and customer-protocol routes are calculated within each CTL. Then, optical path cross-connection information is exchanged between neighboring CTLs using a path signaling protocol, and optical path routes are calculated within each CTL. Finally, CTLs set up their own OXC or forwarder using a switch control protocol.

After the signaling procedure has been completed, PC routers simply cross-connect optical paths to forward data packets. PE routers, on the other hand, in order to select optical paths or access connections, perform an electrical packet forwarding procedure according to the destination address described in the customer-protocol packet header. Consequently, in the lower layer, PC and PE routers composes an optical PC network physically, while, in the higher layer, PE routers composes an electrical PC network logically.

As for typical protocols, the Border Gateway Protocol (BGP)[15] / the Open Shortest Path First (OSPF)[16], the Label Distribution Protocol (LDP)[17] / the Resource reSerVation Protocol (RSVP)[18] and the Generalized Switching Management Protocol(GSMP)[19] is used for an electrical routing protocol, a path signaling protocol and a switch control protocol, respectively. They comprise the Generalized MultiProtocol Label Switching (GMPLS) protocol suite[20].

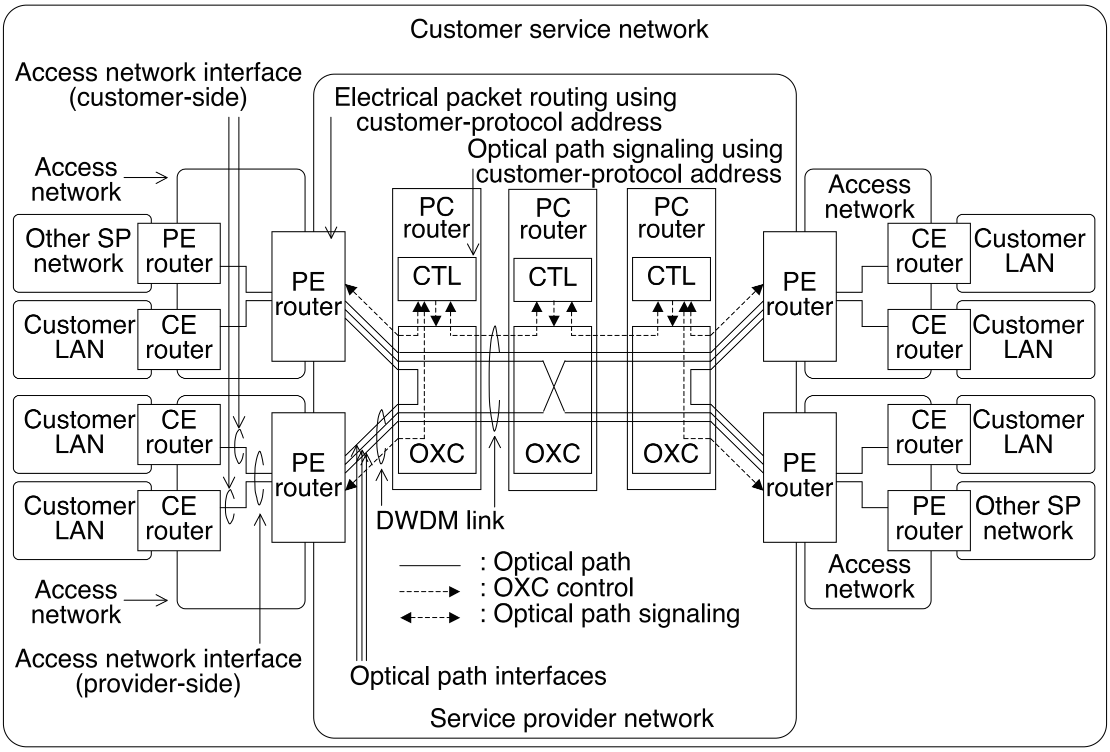

Figure 2.1: Reference network model for multilayer data forwarding

2.3 Related technologies

In this section, the connectionless network emulation technologies using optical paths are shown as the related technologies. They comprise the optical path cross-connect scheme and electrical packet forwarding scheme described in Subsection 2.3.1 and 2.3.2, respectively.

2.3.1 Optical path cross-connection

The simple scheme to emulate a connectionless network using optical paths is to allocate optical paths in a full mesh topology between all PE routers as shown in Fig.2.2. There are three key optical networking issues.

The first issue is the heavy processing load of the customer-protocol routing required for optical path signaling. Although data packets are forwarded using optical paths, the customer-protocol address still needs to be used to determine an optical path route in the signaling procedure.

In an optical path network, an OXC controller may handle a large number of customer-protocol routes, because optical path signaling is based on destination-based customer-protocol routing. For example, in the Internet, a border router in an autonomous system (AS) should be able to handle more than a hundred thousand of customer-protocol routes[1].

Even if the number of PE and PC routers is very small, the number of customer-protocol routes cannot be reduced because the number of customer-protocol destinations is constant. To solve this problem, routing information for the optical path signaling should remain closed in the SP network because optical paths are established only between PE routers.

The second issue is the large number of optical paths. To ensure full reachability among PE routers by means of optical paths alone, the paths would need to be arranged in a mesh topology, regardless of traffic demands.

However, this arrangement may result in low utilization of each path. For example, each OXC would have to handle a large number of broadband optical paths even if the amount of traffic on some paths were small. In addition, PE routers equipped with only a few optical path interfaces could not be attached to a large-scale network composed of many PE routers, because the lack of interfaces would make it impossible to maintain full reachability. To solve this problem, the reachability should be retained in a connectionless manner where edge-to-edge paths are not necessarily required.

The third issue is the degradation of effective performance in the SP network. Mesh-structured optical paths provide only a fixed bandwidth between PE routers regardless of performance requirements. On the other hand, tree-structured optical paths concentrate traffic at the tree's root, which may become a performance bottleneck. To solve this problem, optical paths should be distributed appropriately, according to traffic demands.

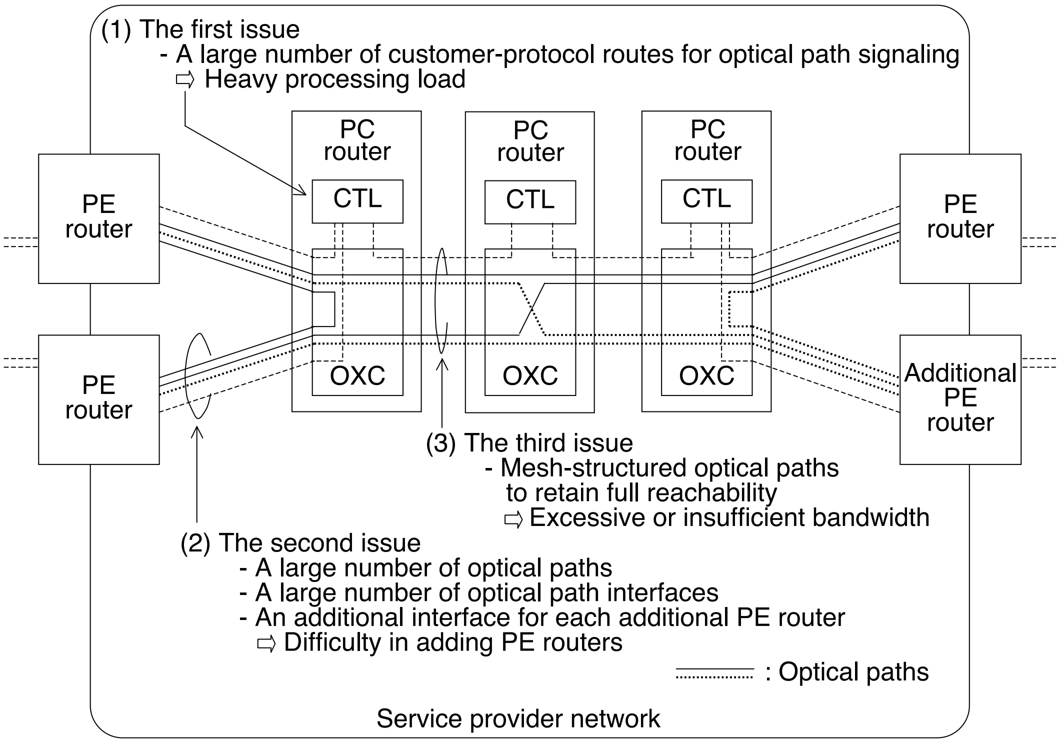

Figure 2.2: Optical networking issues

2.3.2 Electrical packet forwarding

In a full-mesh optical path network, electrical routes should be also established in a full mesh topology between all PE routers as shown in Fig.2.3. There are two key electrical networking issues.

The first issue is the heavy processing load of customer-protocol packet forwarding. In the customer-protocol routing plane where customer-protocol routing table is created using a routing protocol, a PC router and several PE routers can be arranged in a hub-and-spoke topology. In this topology, the processing load of customer-protocol routing is concentrated in the hub PC router and this limits the number of spoke PE routers.

On the other hand, each spoke PE router can simply route optical or electrical paths towards the hub PC router. Here, a simple customer-protocol route towards the hub is called a default route. This route is effective in reducing the processing load arising from customer-protocol routing in a PE router.

However, in the customer-protocol packet forwarding plane where customer-protocol packet forwarding table is created to use every optical path arranged in a mesh topology, each PE router needs to divide a default route towards a PC router into multiple customer-protocol routes towards each PE router. This means that each PE router needs to be able to handle as many customer-protocol routes as are handled by such as AS border routers.

In order to solve this problem, a default route should also be established in the customer-protocol packet forwarding plane.

The second issue is degradation of the whole network performance. When customer-protocol routes are arranged in a mesh topology to keep full reachability regardless of customer-protocol traffic demand, the processing load of managing those customer-protocol routes becomes heavy, and the forwarding performance may be degraded due to a shortage of shared processing resources.

On the other hand, when a default route is established in the customer-protocol packet forwarding plane, each PE router uses only a single optical path and other paths are not used. This means that most optical paths are not used to carry traffic but are used only to retain full reachability.

To solve this problem, customer-protocol routes should be appropriately distributed according to both customer-protocol traffic demands and optical path arrangements.

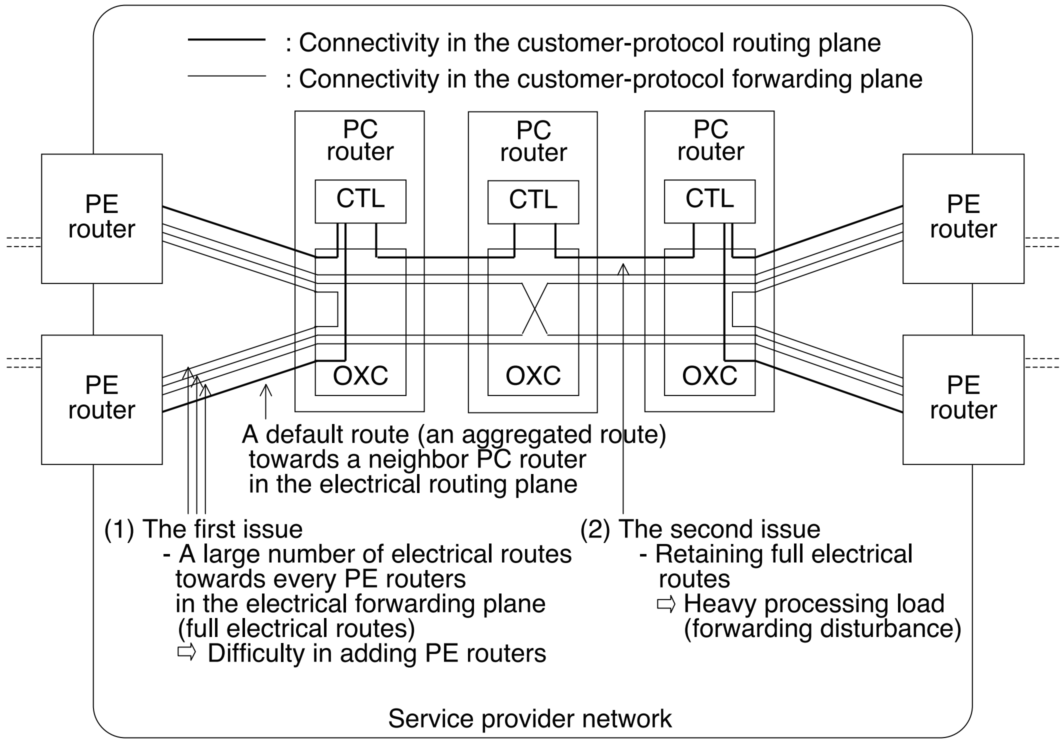

Figure 2.3: Electrical networking issues

2.4 Multi-layer data forwarding technology

In this section, the multi-layer data forwarding technology is proposed. This technology is composed of two elements: a traffic-driven optical networking scheme and traffic-driven electrical networking scheme described in Subsection 2.4.1 and 2.4.2, respectively.

2.4.1 Traffic-driven optical networking

The traffic-driven optical networking scheme uses three key functions: the overlay networking, the connectionless provider-protocol forwarding, and the optical cut-through control.

As a first approach to reducing the processing load of electrical routing required for optical path signaling, the overlay networking is deployed. As shown in Fig.2.4, the SP network is laid under customer-protocol networks, and its address space is separated from their address spaces.

Although customer-protocol addresses are visible to customers, provider-protocol addresses of the SP network are concealed from customers and used only within the SP network. Here, the underlying SP network and concealed addresses are called the provider-protocol network and provider-protocol addresses, respectively.

Thus, PE routers on the forwarding plane perform address mapping between customer-protocol networks and the provider-protocol network so that a large number of visible customer-protocol addresses associated with destination hosts are aggregated into a concealed provider-protocol address associated with the egress PE router accommodating these hosts. This procedure is performed within a PE router using the customer-protocol routing information.

Consequently, optical path signaling can be executed based on the provider-protocol routing information and is independent of the customer-protocol routing information. In addition, the number of provider-protocol routes within the SP network can be reduced to almost the same number as that of PE routers. Consequently, optical paths can be routed using a small number of provider-protocol addresses in spite of a large number of customer-protocol addresses.

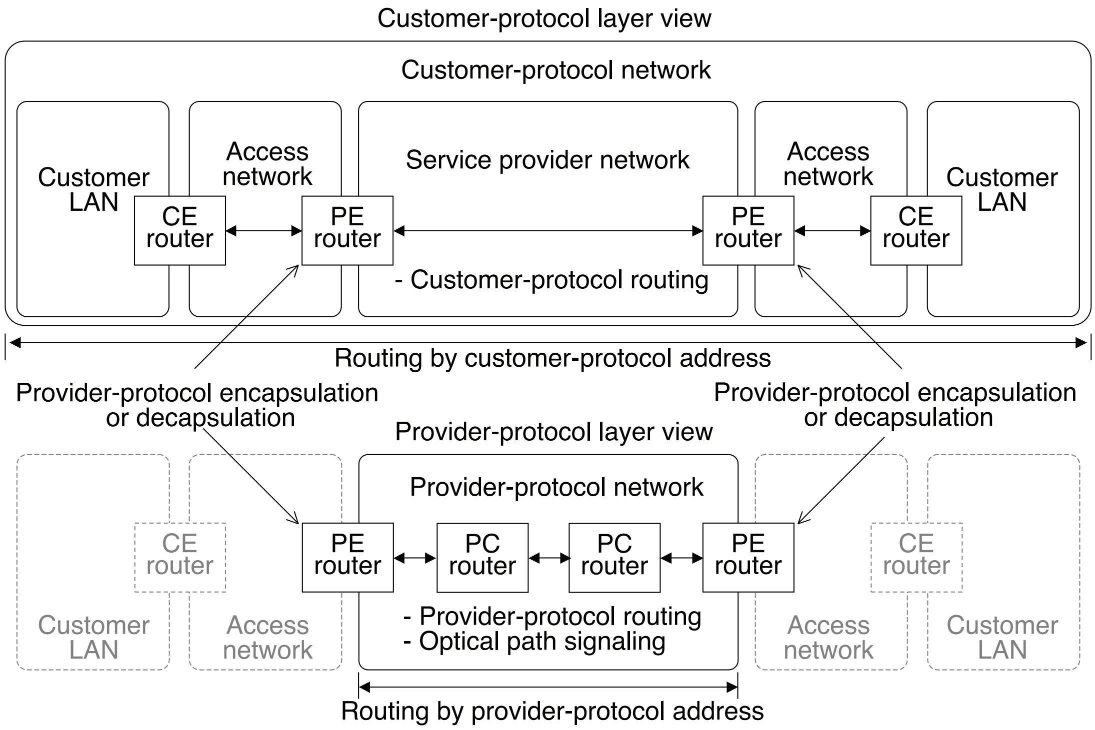

Figure 2.4: Overlay networking

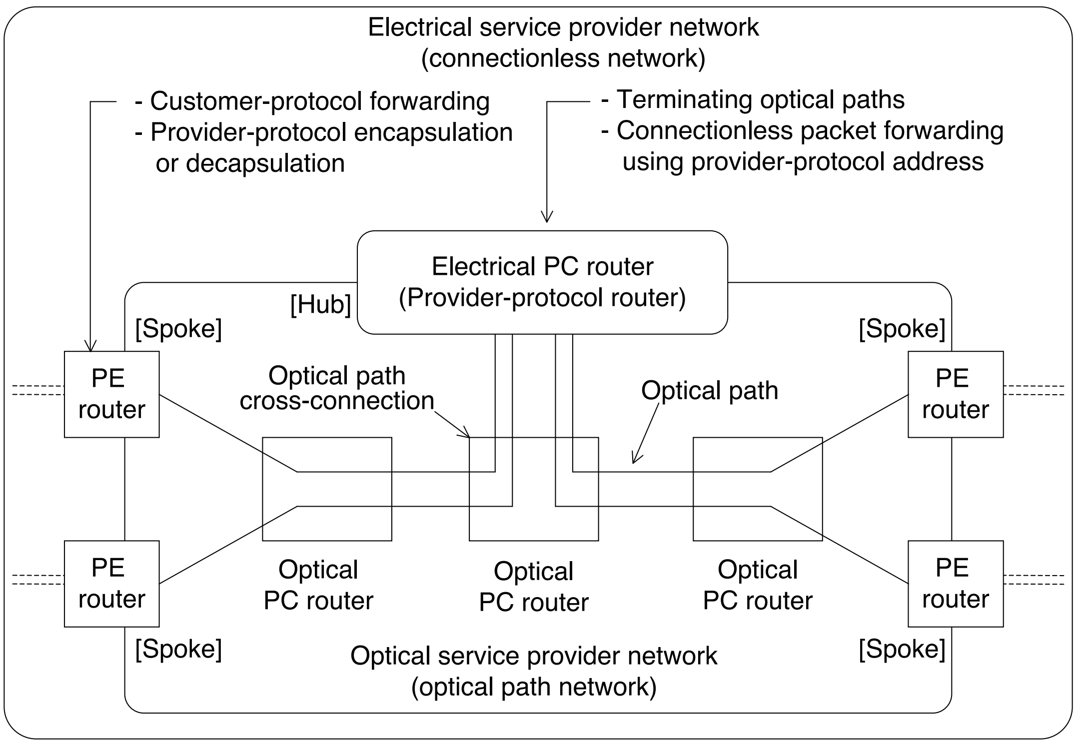

Figure 2.5: Electrical packet forwarding

As a solution to the second issue, the need to reduce the number of optical paths, the electrical packet forwarding function is added to the optical network. As shown in Fig.2.5, the provider-protocol network is logically divided into two layers: the higher layer is the electrical packet forwarding layer and the lower layer is the optical path cross-connect layer.

In the electrical packet forwarding layer, in order to retain full reachability among PE routers with a small number of optical paths, a provider-protocol router is deployed as an electrical PC (E-PC) router.

On the other hand, in the optical path cross-connect layer, optical paths are established between an E-PC router and PE routers and these are arranged logically in a hub-and-spoke topology with an E-PC router at the hub. Here, the number of optical path interfaces in the hub E-PC router limits the number of spoke PE routers.

When multiple E-PC routers are used to accommodate a large number of PE routers, they can be also distributed in a hub-and-spoke topology to reduce the number of terminated optical paths at spoke E-PC routers.

Ingress PE routers perform provider-protocol encapsulation[21]. The provider-protocol address assigned to the egress PE router is resolved from the destination customer-protocol address in the packet header and the original packet is encapsulated into a provider-protocol packet destined for the resolved provider-protocol address. The output optical path is further resolved from the destination provider-protocol address.

The intermediate E-PC routers terminate optical paths and forward provider-protocol packets along paths in a connectionless manner where the output optical path is resolved from the destination provider-protocol address. Egress PE routers, which terminate optical paths, perform provider-protocol decapsulation to terminate provider-protocol routes. The extracted original customer-protocol packets are forwarded towards CE routers according to the destination customer-protocol address.

Consequently, the number of optical paths in the SP network can be reduced to almost the same number as that of PE and PC routers. Furthermore, the number of optical path interfaces required for each PE router to retain full reachability can be reduced to only one. Although deploying a provider-protocol router requires additional cost, it can reduce the required costs of both the PE routers and the OXCs. As a result, the total required networking cost is reduced when a large number of PE routers and OXCs are deployed.

As a solution to the third issue, that is suppressing the performance degradation arising from traffic concentration at the hub, optical cut-through control is applied in the provider-protocol network. As shown in Fig.2.6, a network control server (NCS) is deployed to arrange appropriate cut-through optical paths according to provider-protocol traffic demands. Here, cut-through optical paths are not paths which are essential in order to retain full reachability but additional paths, added to improve performance. The NCS is connected to PC and PE routers via the management network in the management plane.

An E-PC router in the management plane classifies transit packets according to the source-destination pair of the provider-protocol address and counts the number of occurrences of each pair. The NCS collects these numbers from E-PC routers and identifies any source-destination pair whose frequency of occurrence exceeds the decision threshold for establishing a path. Then, it triggers the ingress PE router associated with the source-destination pair to establish a cut-through optical path using signaling.

To avoid running short of cut-through path resources, paths that are not being effectively used need to be released. Thus, a PE router in the management plane also counts the number of transit packets at each interface which terminating a cut-through optical path. The NCS also collects these numbers from PE routers and identifies any path for which the number is smaller than the path release decision threshold.

When cut-through paths cannot be established due to a shortage of path resources, the NCS calculates the optimal path arrangement for minimizing the traffic load on the E-PC routers and may replace some paths with new ones depending on the result. In the basic control, the NCS compares flow amount between electrical flows and optical flows. Here, a flow means a kind of traffic that carried between a specific pair of provider edge routers. When the largest electrical flow amount becomes more than the smallest optical flow amount, the corresponding optical path is replaced with the new path established for that electrical flow. Finally, the traffic load on the E-PC routers is minimized and thus congestion is prevented proactively. This control becomes available by decreasing the decision thresholds for path establishing and by increasing that for path releasing so that optical paths can be allocated using all the supplied path resources.

In order to perform frequent path reallocation, overlay networking scheme is necessary to reduce the processing load of optical path signaling. As the result, cut-through optical paths are optimally arranged according to provider-protocol traffic demands, so limiting any performance degradation of the provider-protocol network.

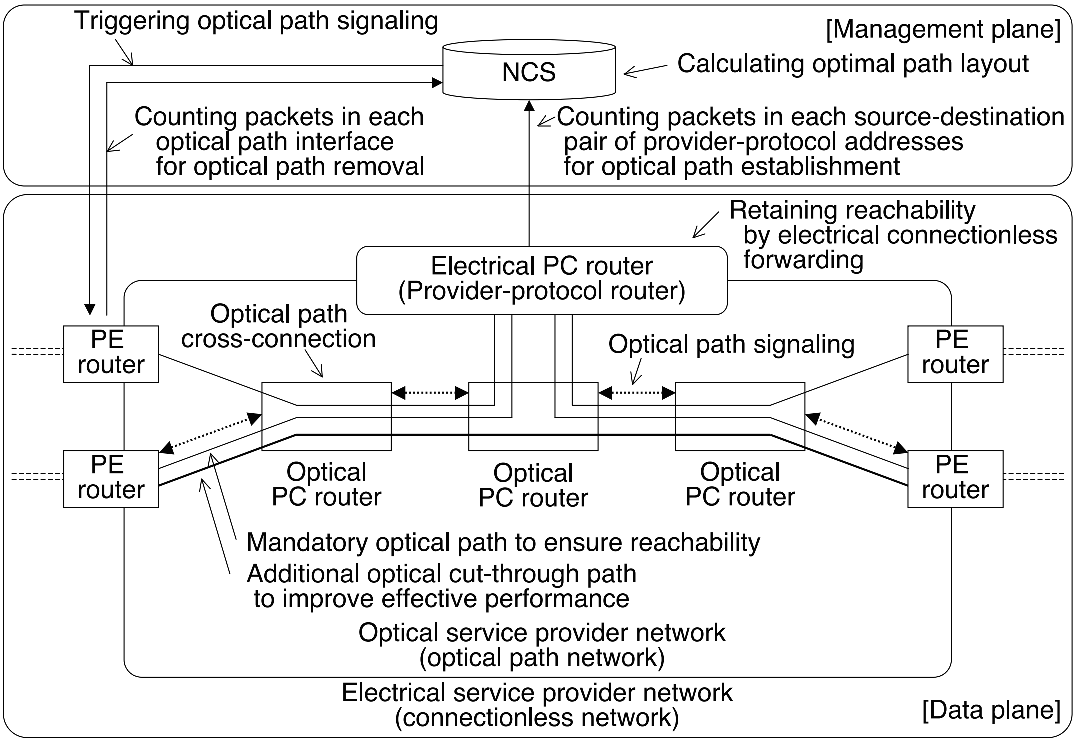

Figure 2.6: Optical cut-through control

2.4.2 Traffic-driven electrical networking

The traffic-driven electrical networking scheme deploys two key functions: hub-and-spoke customer-protocol forwarding and electrical cut-through control.

As a first solution, hub-and-spoke customer-protocol forwarding is used to reduce the processing load of customer-protocol forwarding. As shown in Fig.2.7, PE routers are logically arranged in a hub-and-spoke topology. Here, the hub PE router is called the default forwarder (DF) and a route from a PE router to the DF is called a default route. On the other hand, a route from a spoke PE router to the hub PC router in the provider-protocol layer is called a default provider-protocol route.

In the hub-and-spoke forwarding, the processing load of customer-protocol routing at the hub DF limits the number of spoke PE routers. When multiple hub-and-spoke topologies are established using multiple DFs, they can also be distributed in a hub-and-spoke topology to reduce the processing load of customer-protocol routing at the spoke DFs.

Customer-protocol forwarding routes within the SP network can be controlled using a routing protocol between PE routers including DFs. Customer-protocol forwarding routes towards other SP networks can be also controlled using a routing protocol between PE routers and external PE routers of other SP networks. As a result, the customer-protocol routing information towards other SP networks is also concentrated from PE routers to the DF.

In a hub-and-spoke topology, only a single default route is required for each spoke PE router, while, in a mesh topology, full routes are required for each PE router. Consequently, hub-and-spoke customer-protocol forwarding can reduce the number of customer-protocol forwarding routes required to retain full reachability and thus can reduce the processing load of PE routers.

As a solution to the second issue, the need to avoid performance degradation resulting from traffic concentration at the DF, Electrical cut-through control is used, which is composed of redirection control and purge control.

Redirection control is shown in Fig.2.8, and is used to establish a cut-through electrical route in which any DFs between the ingress and egress PE routers are bypassed.

The DF sends a redirection message to the ingress PE router when it forwards a packet from the ingress PE router to the egress PE router. This message contains customer-protocol forwarding information consisting of the customer-protocol address prefix and provider-protocol address associated with the destination customer subnet and egress PE router, respectively.

An ingress PE router that receives a redirection message adds the contained information to its customer-protocol forwarding table as the redirection entry. Thus, the succeeding packets traveling towards the same destination are forwarded via the cut-through electrical route in accordance with this entry.

Since this control requires certain conditions in which customer-protocol forwarding information should be shared between the DF and the ingress PE routers, it can be deployed only when "connectionless" provider-protocol forwarding is available in the SP network.

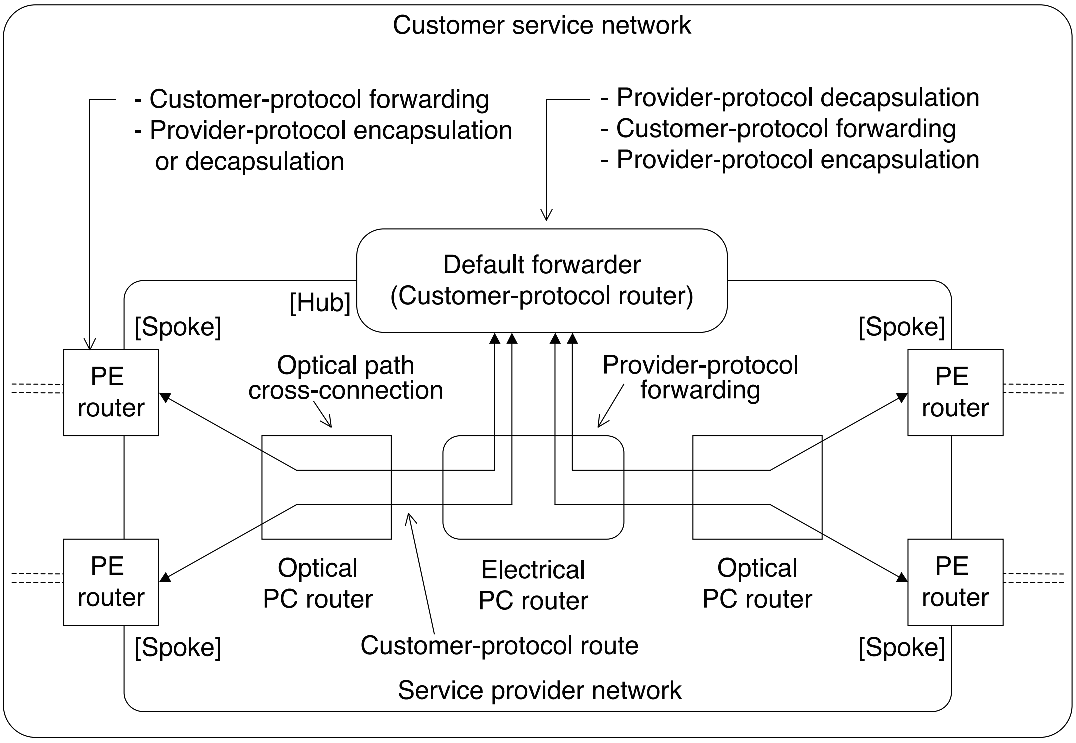

Figure 2.7: Hub-and-Spoke customer-protocol routing

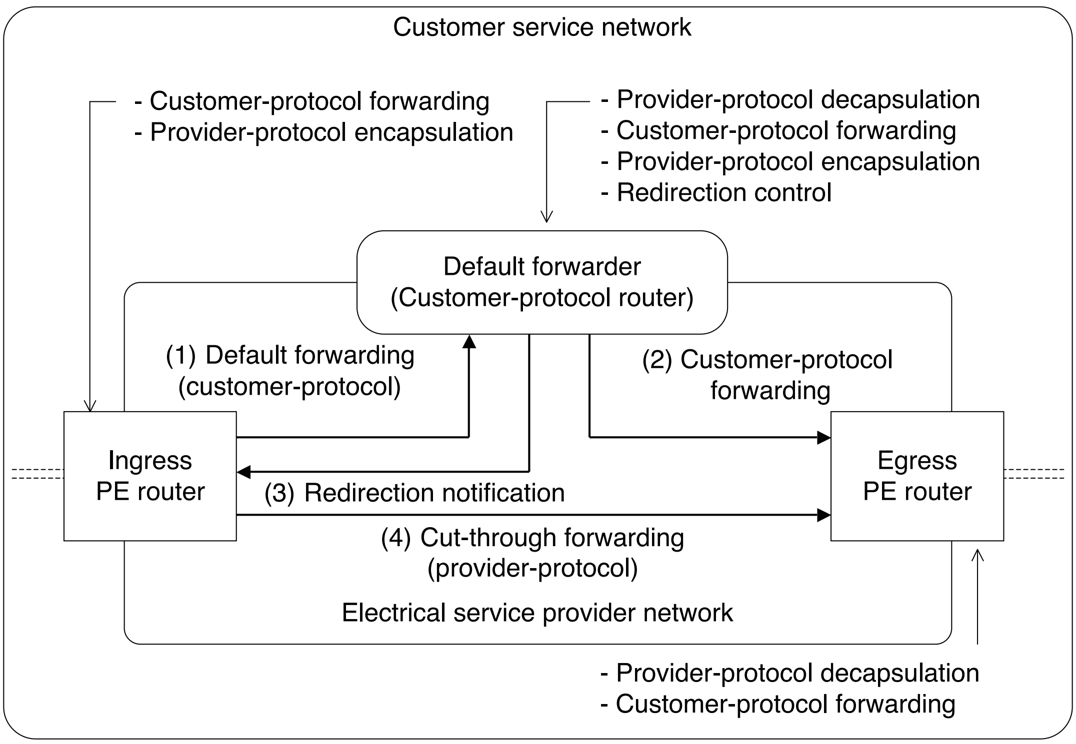

Figure 2.8: Customer-protocol redirection control

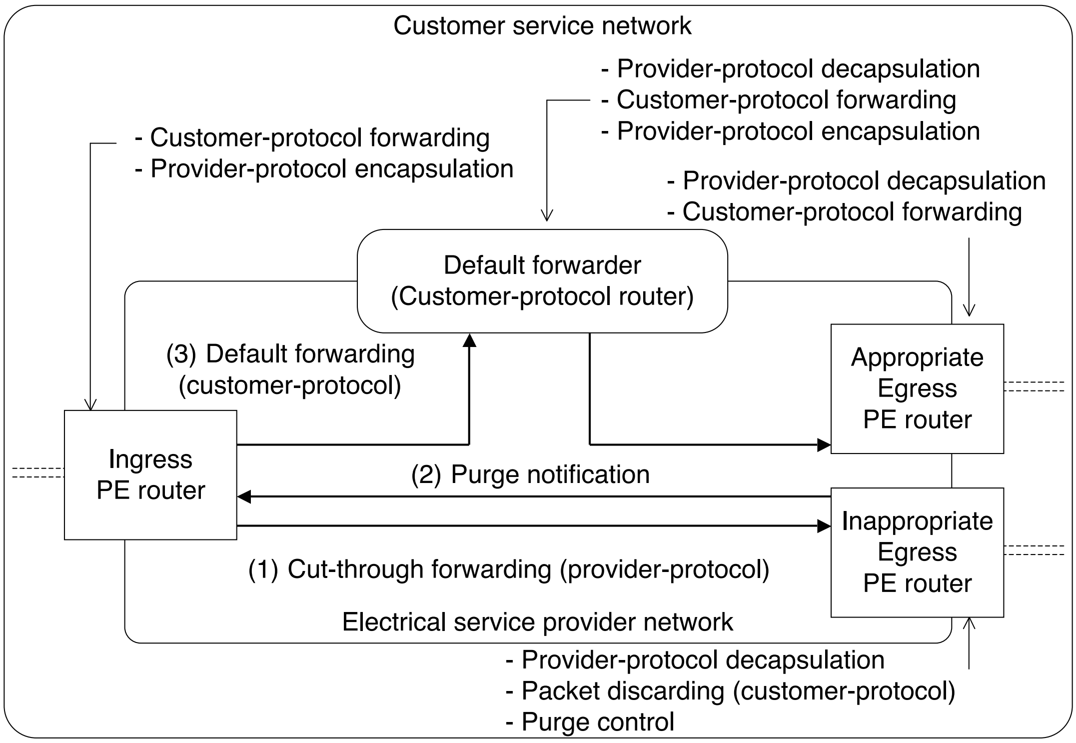

Figure 2.9: Customer-protocol purge control

Purge control, as shown in Fig.2.9, is used for an egress PE router to release a cut-through provider-protocol forwarding route.

The egress PE router sends a purge message to the ingress one when it cannot resolve an access connection towards the CE router associated with the destination customer-protocol address. This message contains only the destination customer-protocol address. The ingress PE router that receives a purge message removes the redirection entry associated with the contained information from its customer-protocol forwarding table. Thus, succeeding packets traveling towards the same destination are forwarded via the default route towards the DF.

Finally, they are forwarded via the appropriate cut-through electrical routes towards the egress PE router because the DF sends a redirection message again. The ingress PE router can also release a cut-through electrical route that has been used rarely by simply removing the corresponding redirection entry.

Since a default route retains full reachability for any destination, cut-through electrical routes can be established according to customer-protocol forwarding demands. In addition, when a significant number of packets are forwarded via a cut-through electrical route, optical cut-through control is also triggered. As a result, cut-through electrical routes and cut-through optical paths are established cooperatively according to customer-protocol traffic demands. This allows a satisfactory performance to be retained for the whole network, even if the number of customer-protocol destinations and PE routers grows.

2.5 Evaluations and discussions

In this section, the scalability of the proposed technology is evaluated from the viewpoint of optical and electrical networking scalability described in Subsection 2.5.1 and 2.5.2, respectively.

2.5.1 Optical networking scalability

The number of optical path interfaces required for each PE router and the number of optical paths required in the SP network were calculated. An optical networking model shown in Fig.2.10 was used for the calculation.

It is assumed that the number of access network interfaces at each PE router (Ia) is constant regardless of the number of PE routers in the SP network (Ne) and that the interface bandwidth is also constant among optical path interfaces and access network interfaces. It is also assumed that the maximum bandwidth demand between any pair of PE routers is less than the bandwidth of the optical path interfaces.

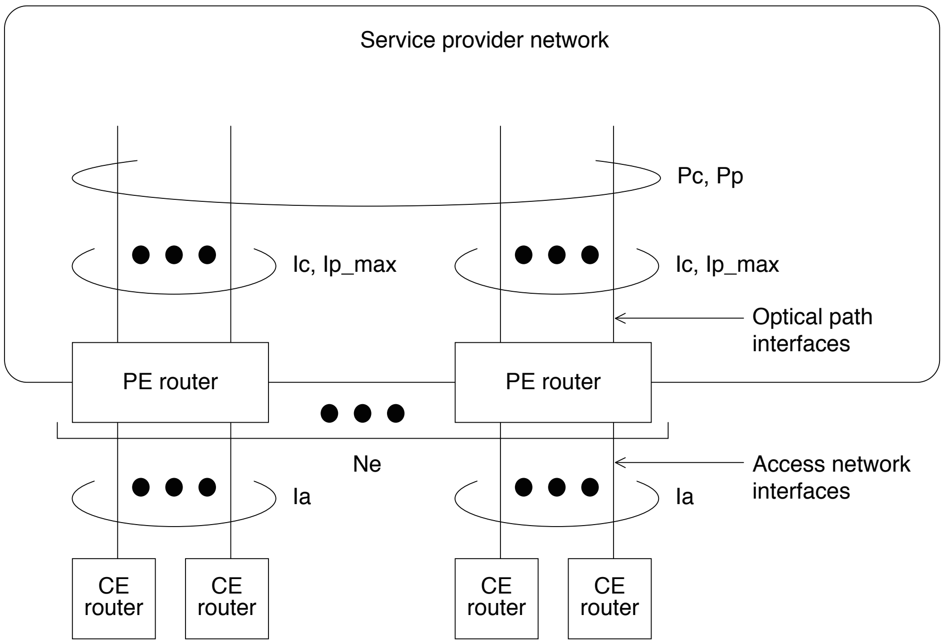

Figure 2.10: Optical service provider network model for evaluation

First, the number of optical path interfaces required for each PE router was calculated. If optical paths were established in a mesh configuration between all PE routers, the number of optical path interfaces required for each PE router (Im) is given by

$$I_m = N_e - 1 \tag{2.1}$$

This means that Im should be increased linearly as Ne increases. In practice, however, Im cannot be increased in an unlimited manner, so Ne should be kept within the limits of Im.

On the other hand, if optical paths are established in a star configuration with an electric PC router as the center hub, the number of optical path interfaces required for each PE router (Is) is given by

$$I_s = 1 \tag{2.2}$$

With a network based on the proposed technology, optical paths are first arranged in a tree topology and cut-through paths are arranged additionally according to traffic exchanging patterns. Here, in each PE router, the number of optical path interfaces can be less than or equal to Ia and Im in order to increase a utilization ratio of each optical path. Thus, the maximum number of optical path interfaces (Ip_max) is given by

$$I_{p\_max} = min\{I_a, (N_e - 1)\} \tag{2.3}$$

This means that Ip_max can be practically constant even as Ne increases. Thus, the number of PE routers in the SP network (Ne) can be increased regardless of the maximum number of optical path interfaces in each PE router (Ip_max).

Second, the number of optical paths in the SP network was calculated. In the mesh configuration approach, the number of optical paths (Nm) is expressed as follows:

$$N_m = \frac{(N_e - 1) \cdot N_e}{2} \tag{2.4}$$

In addition, in the star configuration approach, the number of optical paths (Ns) is expressed as follows:

$$N_s = N_e \tag{2.5}$$

On the other hand, in the proposed approach, the number of optical paths (Np) is expressed as follows:

$$N_p = N_e + \frac{(I_a - 1) \cdot N_e}{2} \tag{2.6}$$

The approaches are compared in Fig.2.11. In this figure, the vertical and horizontal axes show the number of optical paths and the number of PE routers, respectively. Here, the number of access network interfaces at each PE router (Ia) was set to be 15 according to the following assumed conditions: (1) Every PE routers accommodate 10 thousand households, (2) The mean access speed of each household is 15 Megabits per second, (3) Each optical path carries 10 Gigabits per second.

In the full mesh approach, the forwarding capacity of the entire E-SP network exceeds the required throughput because there are an excessive number of optical paths. This means that the costs of the mesh approach are excessive. In contrast, in the star approach, the forwarding throughput is less than that required due to the small number of optical paths.

On the other hand, in the proposed approach, an adequate forwarding throughput can be achieved by ensuring the optimal allocation of cut-through optical paths. This advantage becomes remarkable as the number of PE routers increases.

When the number of supplied paths is constant, in the full mesh approach, reachability may not be maintained because of the path resource shortage, while in the star approach, throughput may not be improved because surplus path resources cannot be used effectively. In the proposed approach, optical paths can be allocated to utilize the whole supplied path resources. This feature is effective in stabilizing optical path control.

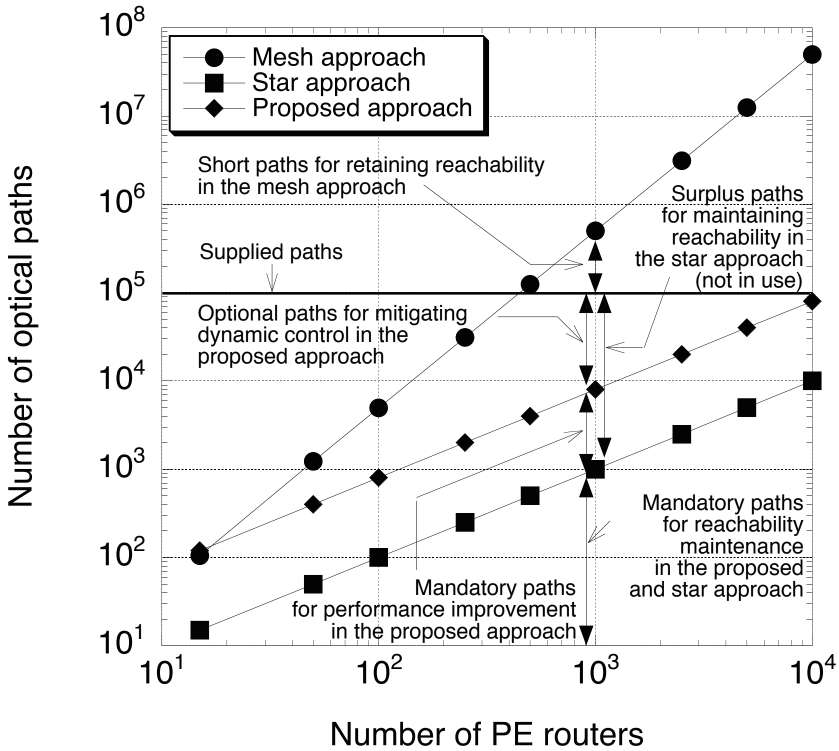

Figure 2.11: Number of optical paths

Some technologies[22][23][24] can also allocate optical cut-through paths, while their scopes are most focused on how to optimize path layouts. In order to achieve dynamic path allocation, lightweight control is important. Thus, as the approximated processing amount of optical path signaling, the number of provider-protocol signaling routes was estimated.

In the basic approach, which is called the peer approach, the SP network is connected with other SP networks so that the customer-protocol routing information is poured into the provider-protocol routing information. Thus, the number of provider-protocol signaling routes is almost the same as that of customer-protocol routes.

On the other hand, in the overlay-based proposed approach, the SP network is connected with other SP networks so that the customer-protocol routing information is not poured into the provider-protocol routing information. Thus, the number of provider-protocol routes is almost the same as that of PE routers.

Those numbers are shown in Fig.2.12. In this figure, the vertical and horizontal axes show the number of electrical routes for optical path signaling and the number of PE routers, respectively. The number of routes in the proposed approach is always less than that in the peer approach when the number of PE routers is less than a hundred thousand. In addition, provider-protocol routes change rarely, while customer-protocol routes fluctuate frequently. As the consequence, the proposed approach is superior to the peer approach from the viewpoint of the processing amount of optical path signaling.

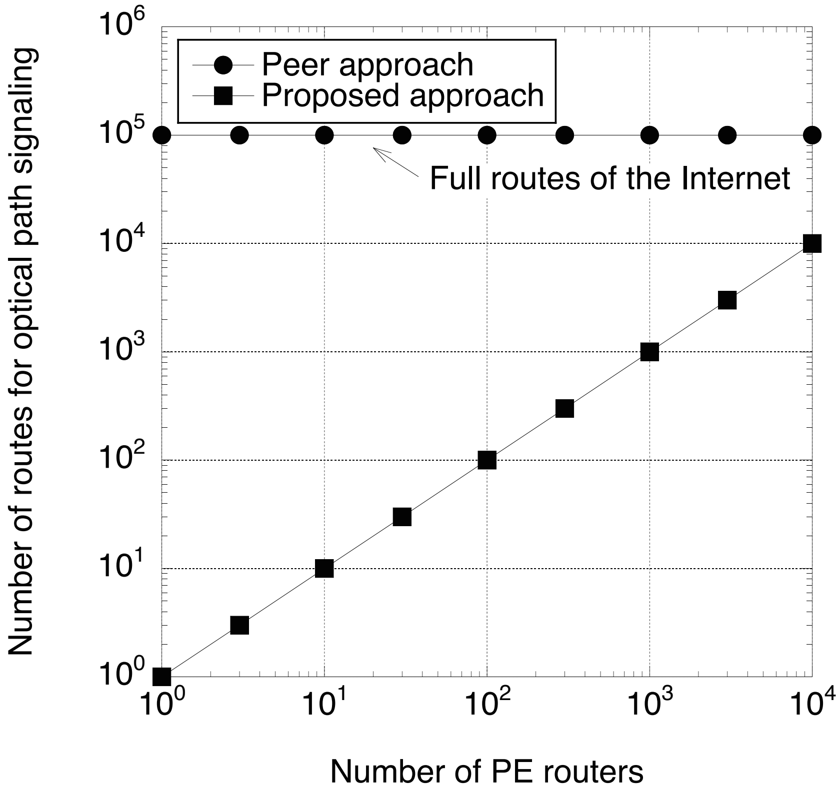

Figure 2.12: Number of routes for optical path signaling

2.5.2 Electrical networking scalability

To evaluate electrical networking scalability, the number of customer-protocol forwarding routes required for each PE router to retain full reachability in the customer-protocol forwarding plane was calculated. An electrical networking model shown in Fig.2.13 was used for the calculation.

In the connectionless network emulation technology using optical paths, which is called the full-routing approach, a default route in the customer-protocol routing plane is divided into a number of customer-protocol forwarding routes in the customer-protocol forwarding plane. Since divided routes are arranged in a mesh topology, the number of routes handled by each PE router (Rc) is the same as that handled by such as the Internet backbone routers (Ri); typically this is more than a hundred thousand routes[1].

$$Rc = Ri \quad (Ri > 100,000) \tag{2.7}$$

On the other hand, in the proposed technology, each PE router is required to handle only a single default route to achieve full reachability. Thus, the number of customer-protocol routes handled by each PE router (Rp) is only one.

$$Rp = 1 \tag{2.8}$$

Consequently, Rp is always less than Rc regardless of the number of PE routers. In addition, their throughputs are almost the same when customer-protocol routes are stabilized. This is because customer-protocol forwarding is performed using forwarding caches generated by means of the customer-protocol redirection control.

In a rough estimation, the required number of cache routes handled by each PE router in a short period (Rr) is the same as the number of customers accommodated by the corresponded PE routers. It has been assumed to be 10 thousand at the scalability evaluations.

$$Rr = 10,000 \tag{2.9}$$

Those routes can be managed lightly in a stateless way. If some cache routes are lost, they can be generated as soon as required by means of the electrical cut-through control.

Those numbers are shown in Fig.2.14. In this figure, the vertical and horizontal axes show the number of routes for packet forwarding and the number of PE routers, respectively. The number of routes in the proposed approach is always less than that in the full-routing approach. In addition, the cache routes in the proposed approach are changed as required of sender customers, while the full routes in the full-routing approach are fluctuate frequently in spite of senders' demands. Therefore, the proposed approach is superior to the full-routing approach from the viewpoint of the processing amount of packet forwarding using cut-through optical paths.

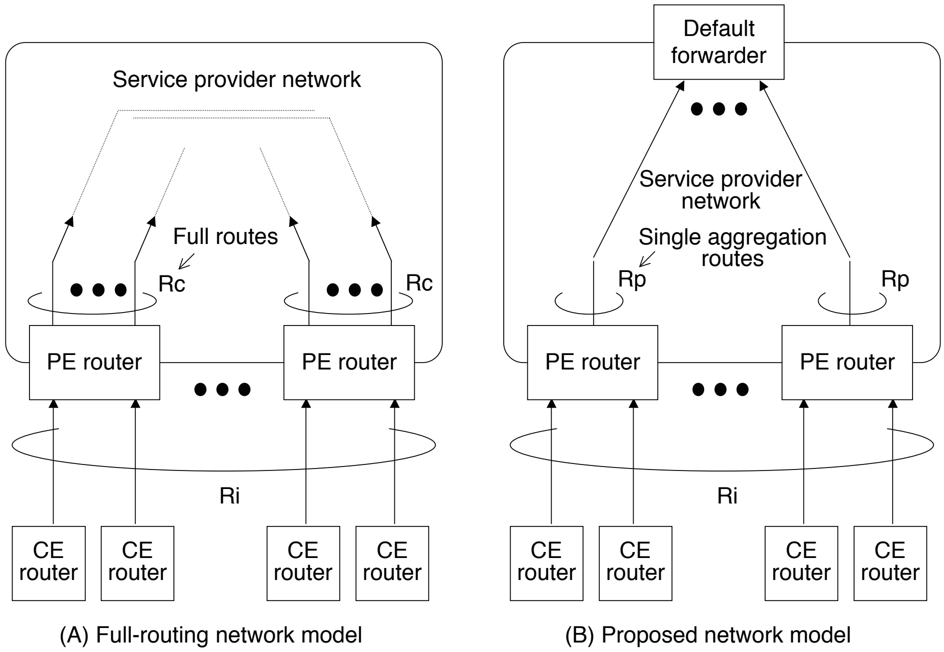

Figure 2.13: Electrical service provider network model for evaluation

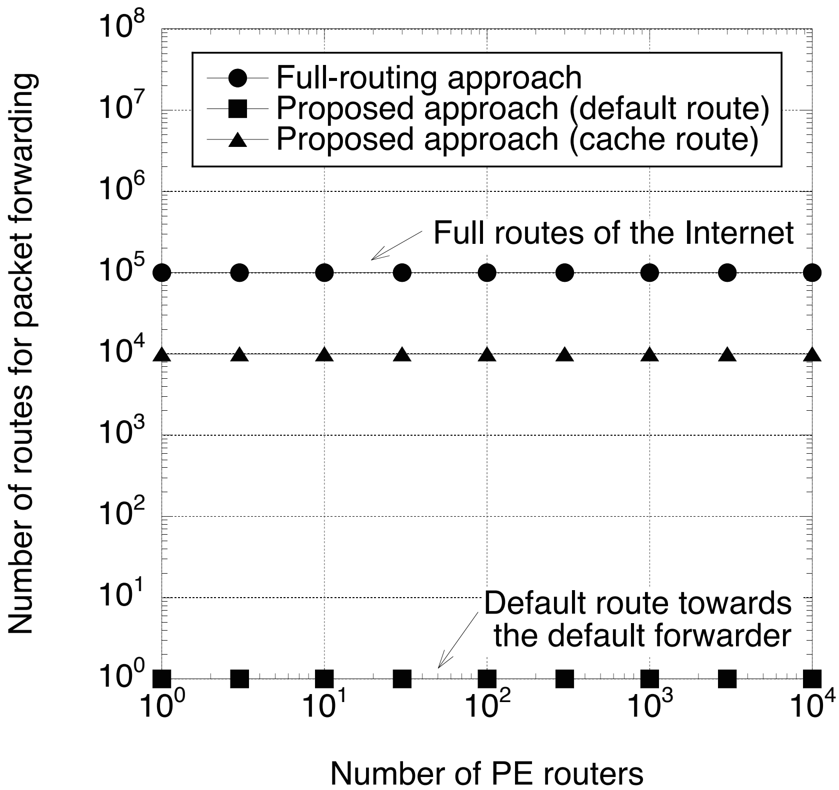

Figure 2.14: Number of routes for packet forwarding

2.6 Conclusion

The connectionless network emulation technology using optical paths is attractive to improve throughput of best-effort services, while the original full-mesh path approach is not scalable. In order to solve this problem, the multilayer data forwarding technology composed of the traffic-driven optical networking scheme and the traffic-driven electrical networking scheme is effective. In the former scheme, reachability is retained by tree-shaped optical paths and throughput is improved by allocating cut-through optical paths. On the other hand, in the latter scheme, reachability is retained by tree-shaped electrical routes and throughput is improved by allocating cut-through electrical routes. For both these, cut-through control is performed reactively, according to traffic demands, and the two work closely with each other. This is effective in maintaining high throughput economically. The results of mathematical analysis have shown that the number of required optical paths in the network can be adjusted according to traffic demand because of the optical cut-through control. In addition, due to the overlay networking, the number of optical path signaling routes to be handled by each provider edge router can be reduced to be the same as that of provider edge routers in the network. Furthermore, owing to the electrical cut-through control, the number of packet forwarding routes to be handled by each provider edge router can be reduced to be the same as that of accommodated customers by each router. On the other hand, in the peer-based basic approach, both numbers are almost the same as that of the Internet full routes. As the result, the proposed technology can provide best-effort data forwarding services with achieving high network throughput and scalability.

Chapter 3

Multi-priority path allocation

In this chapter, a multi-priority path allocation technology is proposed. This technology is designed to offer a bandwidth-reserved data forwarding service and a best-effort data forwarding service simultaneously. An optical path network is attractive because of its broadband feature, while bandwidth resource sharing between optical paths is difficult. In order to solve this problem, the proposed technology first allocates optical paths for the best-effort service as much as possible and then allocates those for the bandwidth-reserved service as required. In order to allocate a sufficient number of bandwidth-reserved service paths, best-effort service paths that interfering bandwidth-reserved service paths are released even in the middle of the communications and the rest of traffic to be carried using the released paths is carried by means of the electrical network. According to the results of the experiments using prototype systems, the proposed technology is feasible to provision the bandwidth-reserved service without excessive throughput degradation of the best-effort service.

3.1 Introduction

Best-effort data forwarding services have spread for personal users that require economical broadband communications. In addition, bandwidth-reserved data forwarding services have also attracted for enterprise users that require reliable and high-quality communications. Accordingly, a network service provider should provision multiple services. Here, bandwidth resource sharing between best-effort and bandwidth-reserved services is important for improving throughput of the whole network, while bandwidth-reserved service traffic should be carried without interference of best-effort service traffic on account of their service features.

In an electrical packet forwarding network, bandwidth resource sharing can be achieved packet-by-packet and bandwidth-reserved service packets can be forwarded without interference of best-effort service packets by means of a packet scheduling scheme based on the packet priority level[25][26].

However, in an optical transmission scheme based on a constant-bit-rate (CBR) path, bandwidth resource sharing between paths is difficult. Then, existing paths for the best-effort service may block allocation of new paths for the bandwidth-reserved service and thus the total throughput of the bandwidth-reserved service may be insufficient.

Optical path networks are still attractive because of their broadband feature. Thus, in order to solve the resource sharing problem, in this chapter, a multi-priority path allocation technology is proposed[9]. In this technology, best-effort service paths are first allocated as much as possible. Then, bandwidth-reserved service paths are allocated on demand so as to replace interfering best-effort service paths[27]. The rest best-effort traffic to be carried using the released paths is carried by means of the electrical network so as to complete the communications. As the consequence, this technology achieves sufficient provision of the bandwidth-reserved service without excessive throughput degradation of the best-effort service.

In this chapter, the reference network model is shown in Section 3.2 and the related technologies are summarized in Section 3.3. Then, the proposed technology is described in Section 3.4 and its feasibility is evaluated in Section 3.5. Finally, a brief conclusion is provided in Section 3.6.

3.2 Reference network model

The reference network model used to study the multi-priority path allocation technology is shown in Fig.3.1. In the data plane, this model is composed of an optical service provider (O-SP) network, an electrical service provider (E-SP) network, access networks and customer LANs. In the management plane, the network control server (NCS) manages those networks centrally.

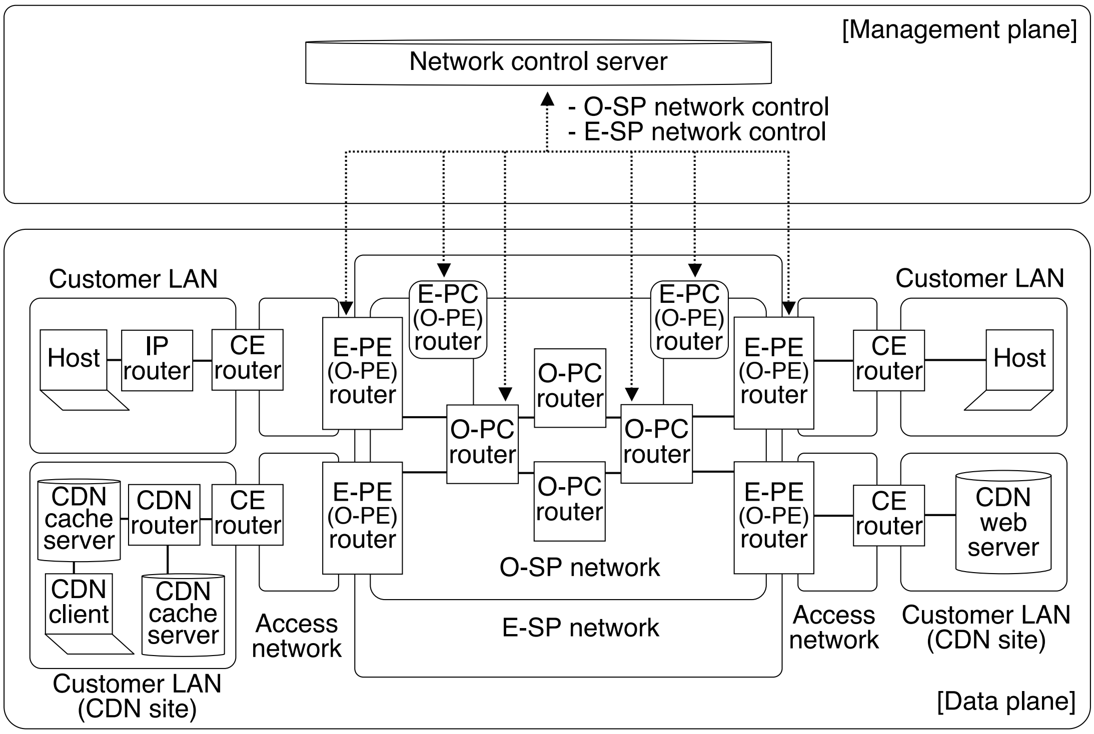

Figure 3.1: Reference network model for multi-priority path allocation

The O-SP network shown in Fig.3.2 offers optical paths[6] dynamically as high-speed data links. This network comprises optical provider core (O-PC) routers and optical provider edge (O-PE) routers. They are connected to each other using the Dense Wavelength-Division Multiplexing (DWDM)[14] links.

An O-PC router comprises an optical path cross-connect (OXC) and its controller (CTL)[12]. Although O-CTLs are also required for the O-PE routers which terminate the optical paths, they are separated from the O-PE routers and centralized into the NCS. Implementation examples of optical network protocol suites are the Generalized MultiProtocol Label Switching (GMPLS) suite[20] and the Optical User-Network Interface (O-UNI) suite[28]. The Path Computation Element Protocol (PCEP) suite[29] is an example implementation of a part of the NCS architecture.

The E-SP network shown in Fig.3.3 is located over the O-SP network and provides data forwarding reachability for all destinations economically. This network is composed of electrical provider core (E-PC) routers and electrical provider edge (E-PE) routers, each of which corresponds to an O-PE router. These E-PC and E-PE routers are connected to each other using optical paths and cooperate with each other using electrical packet forwarding protocols.

An E-PE router accommodates many customer local area networks (LANs) within a specific site. Electrical routing functions are separated from both E-PC and E-PE routers. They are also centralized in the NCS. This NCS controls electrical packet forwarding functions deployed in the E-PC and E-PE routers.

Implementation examples of electrical network protocol suites are the Internet Protocol version 6 (IPv6) suite[30] and the MultiProtocol Label Switching (MPLS) suite[31]. In addition, those for the NCS to control the networks are the Simple Network Management Protocol (SNMP) suite[32] and the FORwarding and Control Element Separation (FORCES) suite[33]. Furthermore, those for the NCS to collect traffic information are the NetFlow[34], the sFlow[35] and the SNMP.

The customer-service networks such as VPNs are located over the E-SP network, access networks and customer LANs. Those customer-service networks offer data forwarding services for customers. They comprise E-PE routers, customer edge (CE) routers and customer host terminals. Implementation examples of customer protocol suites are the IP version 4 (IPv4) suite[36] and IPv6 suite[30].

The application networks are located over the customer-service networks. In order to use various application efficiently, many application networks are configured independently. A typical example is a contents delivery network (CDN)[37] established to offer a high-quality content-access service economically. This network is composed of CDN World-Wide-Web (WWW) servers, CDN cache servers, CDN routers and CDN clients. The CDN routers select an appropriate CDN cache server for a content-access request from a CDN client. This behavior is also effective to reduce traffic below the customer-service network layer.

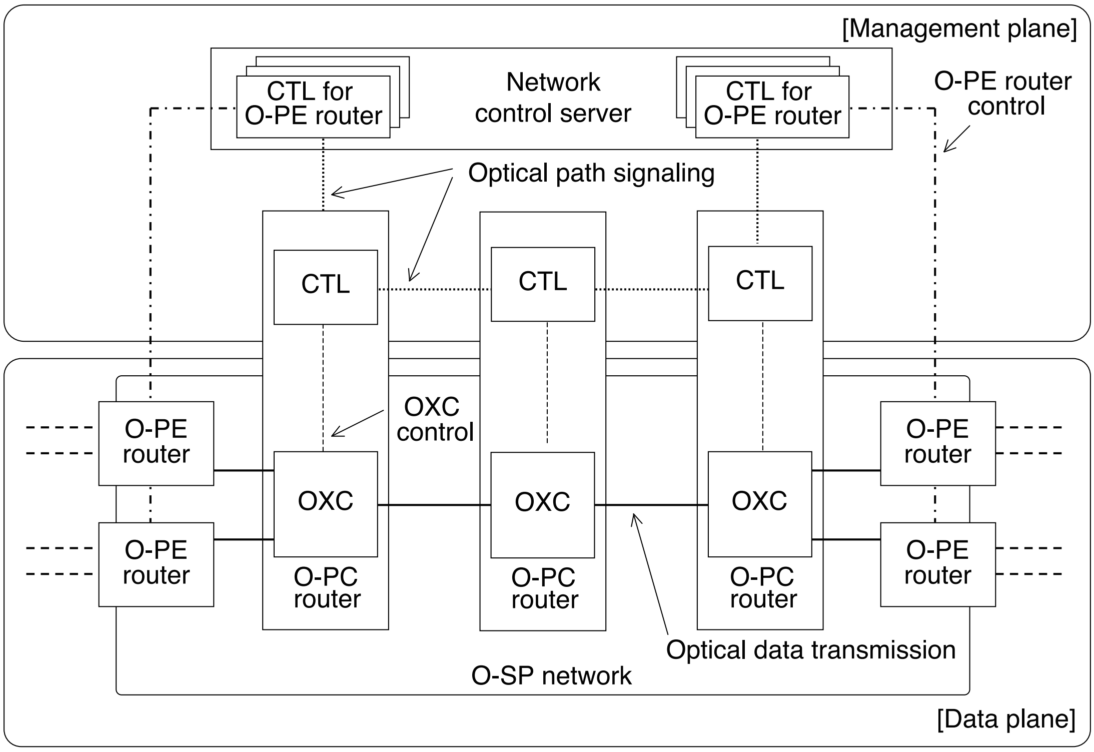

Figure 3.2: Optical service provider network model

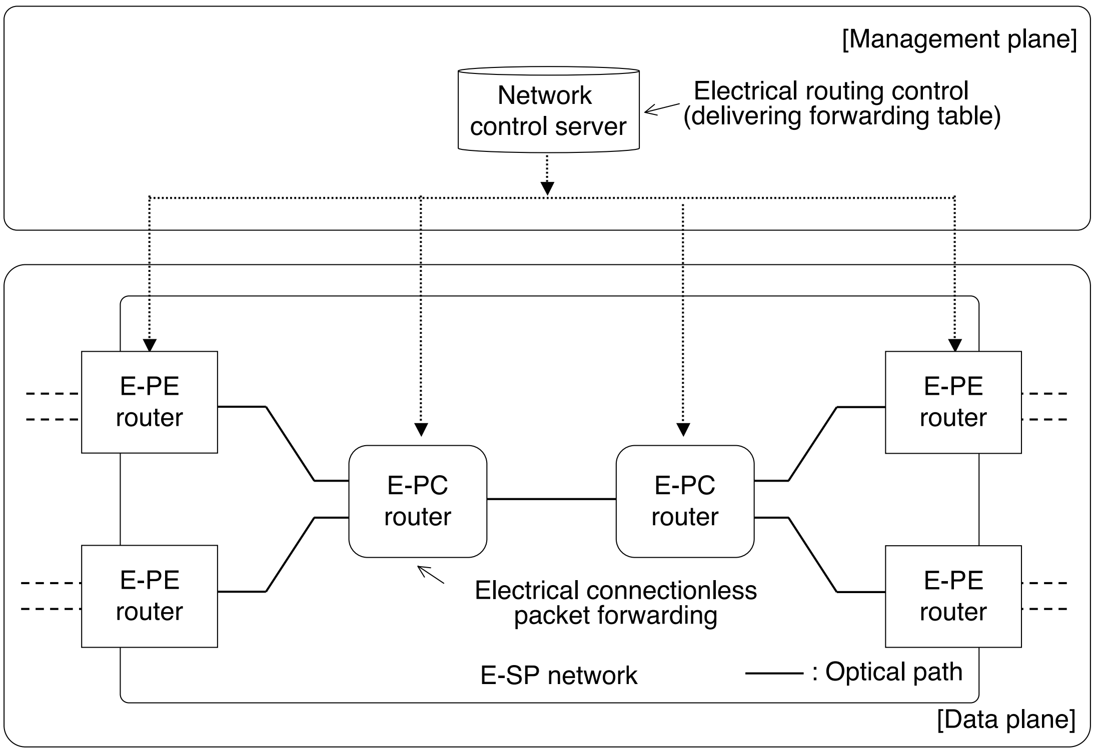

Figure 3.3: Electrical service provider network model

3.3 Related technologies

In this section, the related technologies is described from the viewpoint of intra-layer and inter-layer traffic engineering schemes. First, as the intra-layer schemes, optical traffic engineering, electrical traffic engineering and application traffic engineering are summarized in Subsection 3.3.1, 3.3.2 and 3.3.3, respectively. Then, as the inter-layer scheme, the traffic-driven optical networking scheme is described in Subsection 3.3.4.

3.3.1 Optical traffic engineering

In the optical network layer, it is important to satisfy the various reliability requirements efficiently by means of automatic path protection control. For this issue, two kinds of optical path protections have been proposed. They are the dedicated and shared protections. These protections are selected for each path according to the reliability and cost demands of customers.

In the dedicated protection[38] shown in Fig.3.4, both a working path and a backup path are established and activated simultaneously. An ingress O-PC router in the optical domain then send optical signals through both paths. When a failure occurs in the working path, the egress O-PC router in the optical domain detects it as a signal failure or degradation, and automatically selects the backup path. Optical paths belonging to this protection are bundled in a protected logical link. This protection offers the fastest restoration, but needs dedicated resources for a backup path.

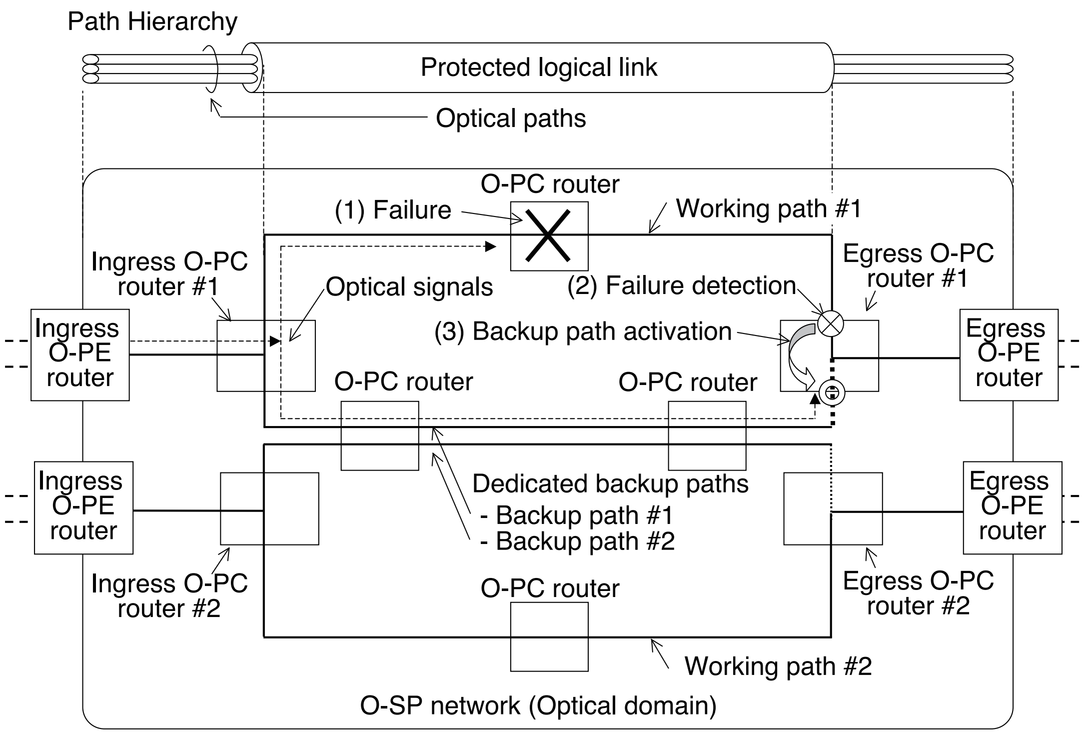

Figure 3.4: Dedicated protection

On the other hand, in the shared protection[39] shown in Fig.3.5, both a working path and a backup path are established at the initial stage, but only the working path is activated in normal operation. Since the backup path is not activated, it can be shared as a backup between several working paths.

In addition, a path segmentation technique is implemented to achieve rapid activation of backup paths. In this technique, a working path is divided into several segments and the shared backup path is also divided and assigned for each segment.

When a failure occurs in one segment, a failure notification is broadcast within that segment. The notified O-PC routers activate the backup path segment and use it to replace the faulty path segment. Here, each segment is defined in such a way that the permissible restoration time can be satisfied. This protection service offers an economical means of path protection, achieved by path resource sharing, while the increase in path restoration time can be minimized by means of path segmentation.

In order to offer the multi-grade protection service, these protections are selected appropriately by means of the centralized control using the NCS. Since the NCS can accept customer requests using such as WWW access interfaces, customer equipments are not required to implement any optical signaling functions.

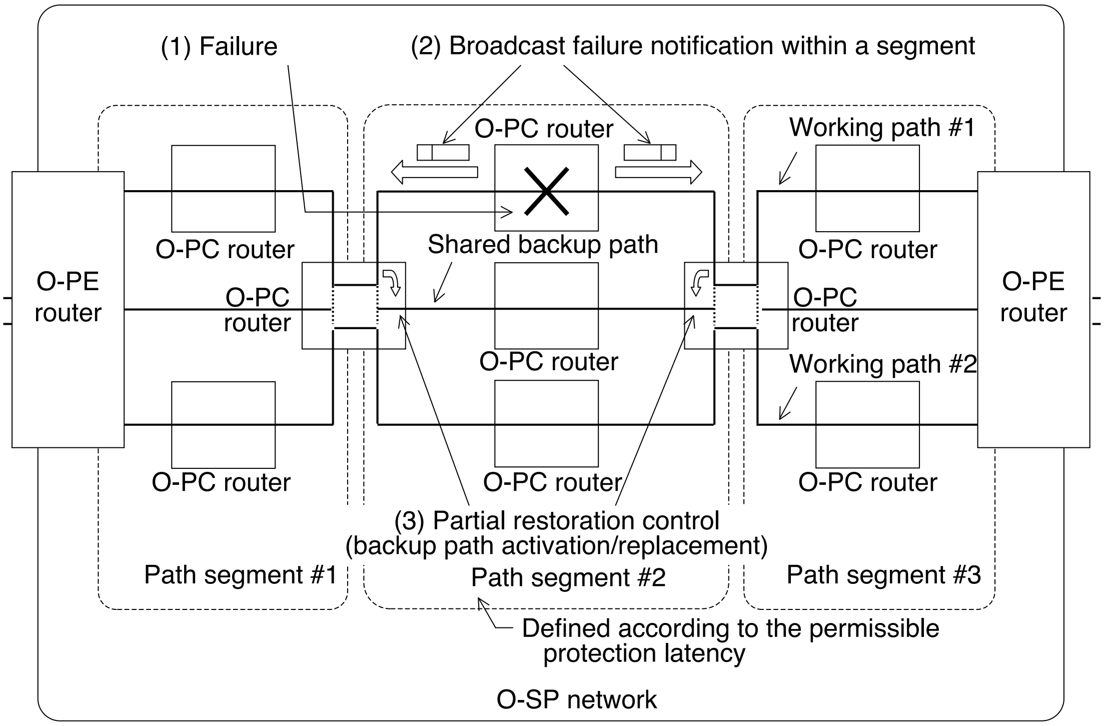

Figure 3.5: Shared protection

3.3.2 Electrical traffic engineering

In the electrical network layer, the traffic load should be balanced between the E-PC routers in order to maximize throughput of the whole network. In addition, when some E-PC router fails, it must be bypassed in order to achieve reliability.

In the electrical load-balancing, shown in Fig.3.6, at the time of initial configuration, multiple addresses are assigned to a single E-PE router and multiple routes are established between the ingress and egress E-PE routers. Here, the NCS calculates the electrical forwarding routes and controls the packet forwarding tables of the E-PC and E-PE routers.

In order to optimize the load balancing, each E-PC router classifies transit packets according to a pair of source-destination addresses and counts the number of these packets. The NCS then collects these numbers from the E-PC routers.

When it detects the failure of an E-PC router or an imbalance in the traffic load between E-PC routers, it tells the ingress E-PE routers to change the routes which they are using to send packets to the egress E-PE routers. The instructed E-PE routers then use alternative addresses to send packets toward the egress E-PE routers. This centralized control is an important to achieve optimal throughput of the whole E-SP network effectively.

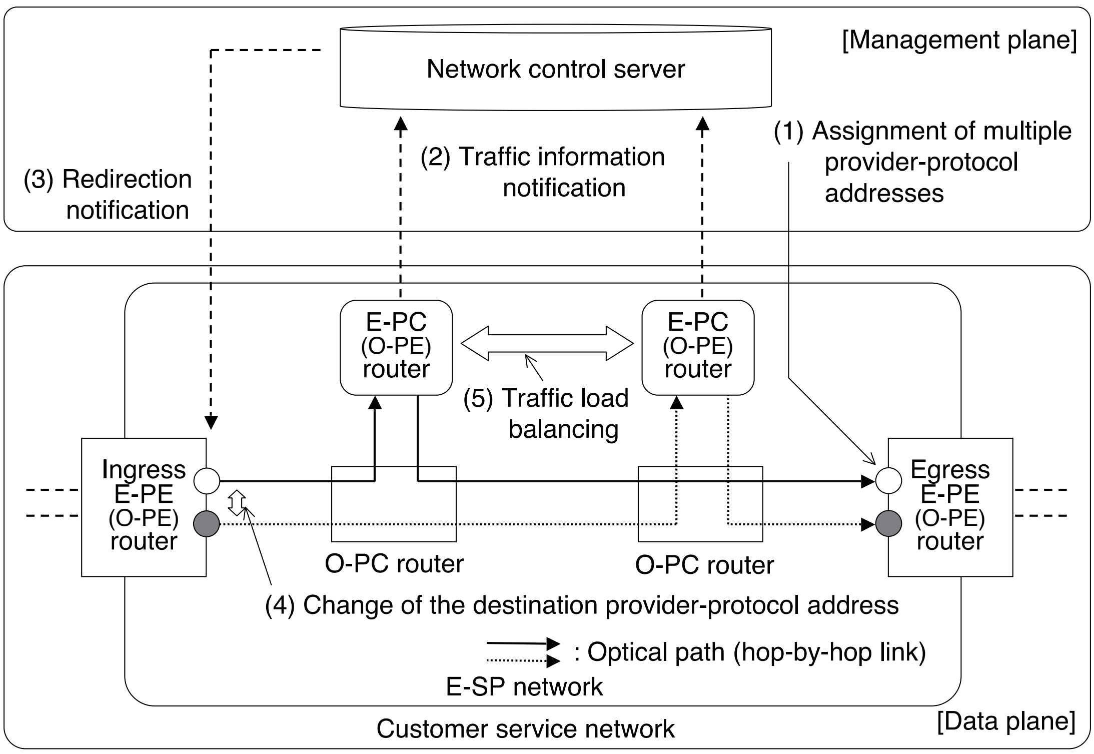

Figure 3.6: Electrical load-balancing

3.3.3 Application traffic engineering

In the application network layer, some traffic can be localized within a site by means of a content-caching approach. This is effective in improving the throughput of the whole network because the traffic load of the E-SP network is reduced. In addition, it is also effective for CDN clients in reducing the latency incurred when accessing WWW content.

In the distributed content-caching, shown in Fig.3.7, multiple CDN cache servers are distributed within a site. Each CDN cache server monitors its processing load. The CDN router collects these values. When a CDN client requests content data, the CDN router selects the route towards the cache server which has the lowest load. In this way CDN clients receive content data from the most appropriate CDN cache server. According to this control, the CDN throughput is improved.

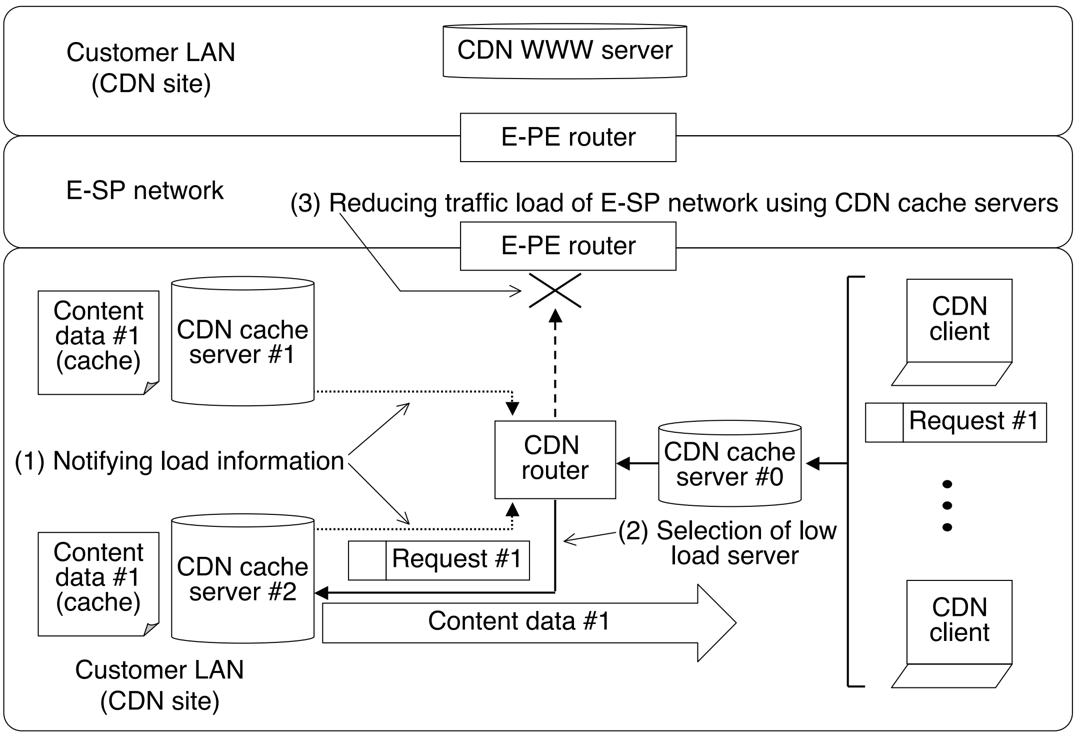

Figure 3.7: Distributed content-caching

3.3.4 Traffic-driven optical networking

The traffic-driven optical networking scheme[8] has been designed to ensure cooperation between the electrical network layer and the optical network layer. In this scheme, shown in Fig.3.8, if the volume of traffic flowing from an ingress E-PE router to an egress E-PE router is small, it is carried by means of an electrical packet forwarding scheme, which ensures that reachability is maintained between all E-PE routers.

On the other hand, if the amount of traffic is large, it is carried using a cut-through optical path established between the specific E-PE routers concerned. Thus, in order to improve both throughput and scalability, optical path layout is optimized dynamically, according to the spatial traffic fluctuation.

The NCS collects traffic information from the E-PC routers. When several E-PC routers are too congested to allow the traffic load to be balanced, the NCS triggers optical cut-through control in order to establish a cut-through optical path between the ingress and egress PE routers. Here, the E-PE routers act as O-PE routers, and the NCS acts as their proxy O-CTLs. Finally, the NCS controls the ingress E-PE router, which is generating a lot of traffic, to map the electrical packet forwarding routes towards the egress E-PE router over the newly established path.

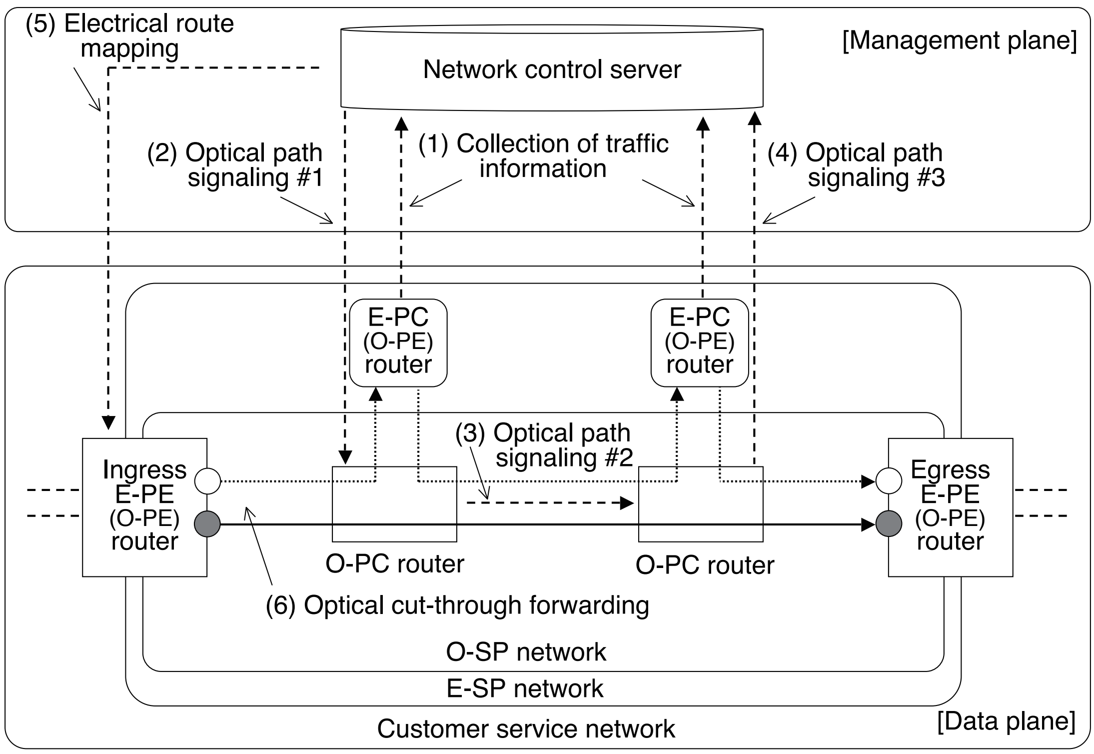

Figure 3.8: Traffic-driven optical networking

In this scheme, the key to optimizing the path placement is the centralized control approach shown in Fig.3.9. The NCS collects traffic information from the E-PE routers in addition to the E-PC routers.

When a new cut-through path cannot be established because all path interfaces are already in use at either routers, the NCS compares the amount of traffic carried by existing cut-through paths with that carried by the E-PC routers. If the flow amount on an existing cut-through optical path is smaller than the flow amount through the E-PC router, the existing cut-through path is removed, and a new path is established for that electrical flow. Since this control reduces traffic load on each E-PC router, communication quality through E-PC routers is also maintained.

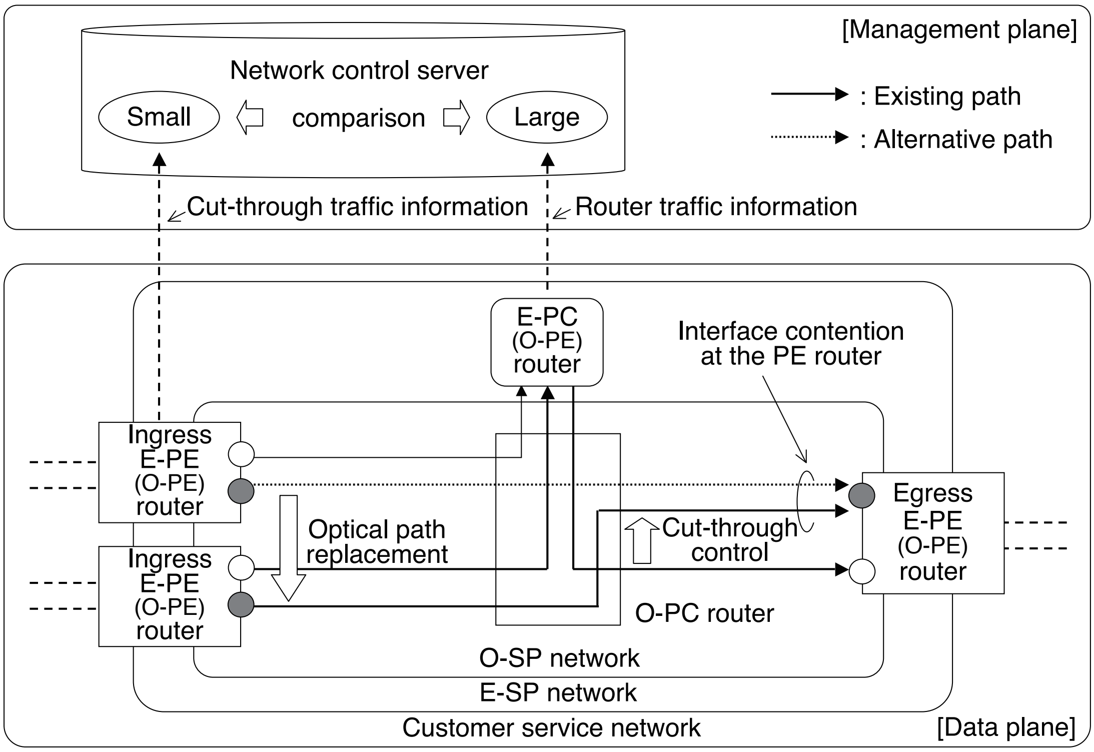

Figure 3.9: Path placement optimization

3.4 Multi-priority path allocation technology

In this section, the multi-priority path allocation technology is proposed. This technology comprises an application-driven optical networking scheme and prioritized path allocation scheme described in Subsection 3.4.1 and 3.4.2, respectively. The former is required to provision a bandwidth-reserved data forwarding service. On the other hand, the latter is required to increase throughput of the bandwidth-reserved service without excessive throughput degradation of the best-effort service.

3.4.1 Application-driven optical networking

The application-driven optical networking scheme is designed to provision a bandwidth-reserved data forwarding service. This scheme enables the application network layer and the optical network layer to cooperate with each other.

In this scheme, shown in Fig.3.10, a cut-through optical path is established in response to an appropriate request by an application and this path carries a large amount of traffic even at the initial forwarding stage. This scheme is effective for SP networks, to prevent transient congestion and to provide high quality communication for applications.

As for inter-layer cooperation, a CDN utilizes optical network as follows:

(1) When the CDN cache server does not contain the requested content, a CDN router selects the original CDN WWW server located at the remote site.

(2) Then the CDN router requests the NCS to establish a cut-through optical path in order to minimize latency.

(3) On receiving the request, the NCS determines the appropriate ingress and egress E-PE routers between the CDN WWW server and the CDN client.

(4) Thus, an optical path is established between the specified E-PE routers.

(5) After the path has been established, the NCS maps electrical packet forwarding routes over this path and sends an acknowledgement to the CDN router.

(6) After the data transfer is completed, the CDN router requests the NCS to remove the path.

According to this procedure, CDN quality can be improved economically even when CDN cache server does not contain the requested content.

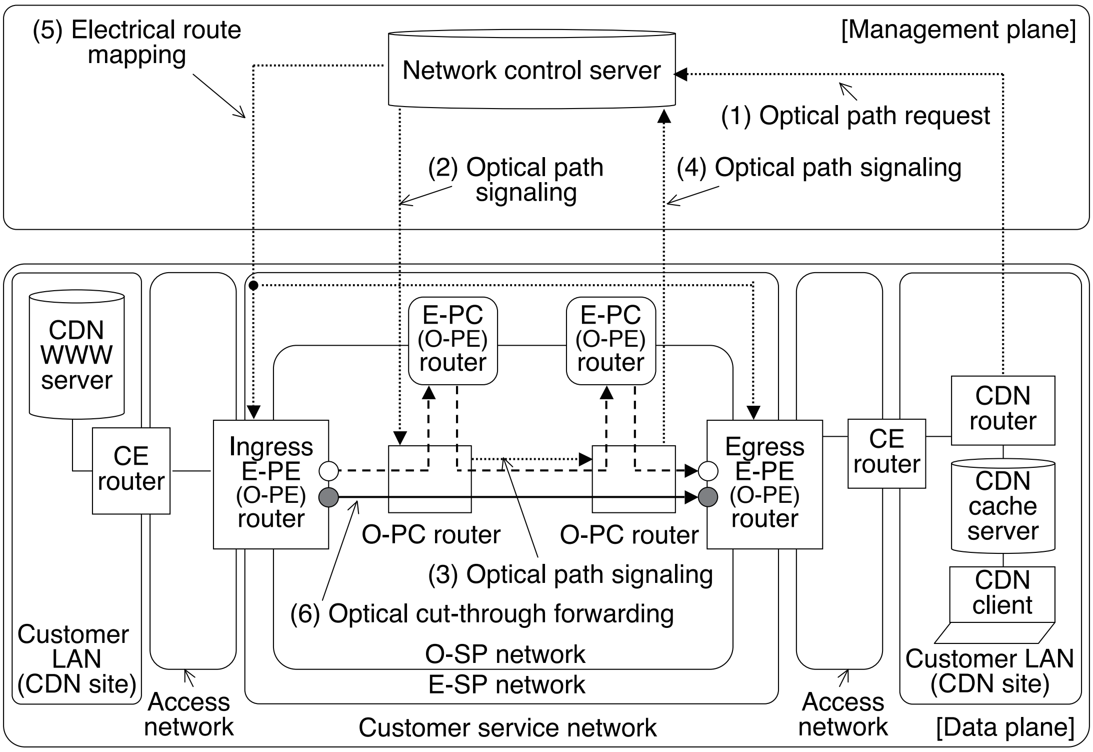

Figure 3.10: Application-driven optical networking

3.4.2 Prioritized path allocation

A prioritized path allocation scheme is designed to arbitrate between the traffic-driven and application-driven optical path requests. In the conventional path allocation scheme, optical paths are established normally in the arrival order of path requests. This order can be changed according to the level of path request priority by means of the conventional priority control scheme.

However, existing traffic-driven paths for best-effort services may block allocation of new application-driven paths for bandwidth-reserved services. This behavior decreases the total throughput of bandwidth-reserved services, while this throughput should be improved from the viewpoint of commercial services.

In order to solve this problem, in this scheme, shown in Fig.3.11, an existing traffic-driven path that is blocking the requested application-driven path is first removed and the requested application-driven path is established.

Traffic to be carried by the removed paths is then carried by means of the electrical network. Accordingly, in the proposed scheme, even if any traffic-driven path is removed, reachability is maintained. When a number of application-driven requests arrival at once, they are admitted in the order of arrival.

This scheme enables traffic-driven paths to be allocated as much as possible at the initial stage. Then, application-driven paths can be allocated so as to replace interfering traffic-driven paths. Consequently, the total throughput of application-driven paths can be improved without excessive degradation of that of traffic-driven paths.

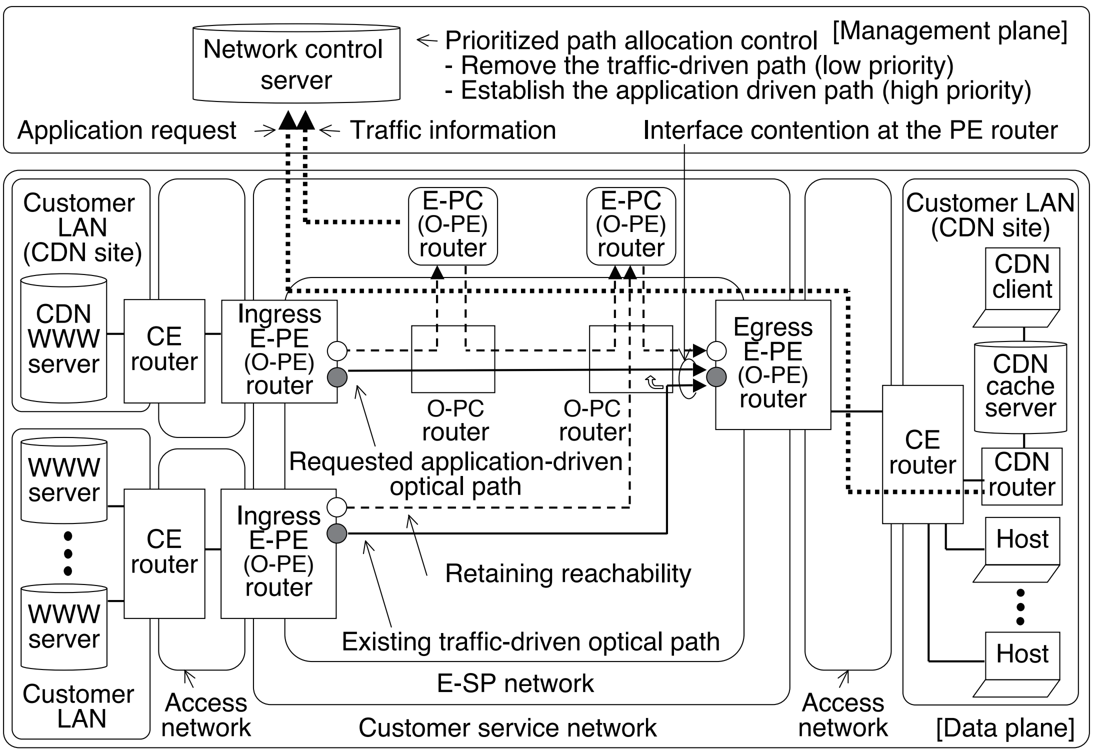

Figure 3.11: Prioritized path allocation

3.5 Evaluations and discussions

The feasibility of the proposed technologies was evaluated using an experimental network composed of prototype systems. The experimental network configuration is shown in Fig.3.12.

In this network, three E-PE routers were connected to each other via six O-PC routers and two E-PC routers. They were controlled using an NCS. In addition, a video server, video client, IP router, CDN router, CDN web server, and three CDN client and three CDN cache servers compose application networks running over the E-SP network. The feasibility was evaluated as follows:

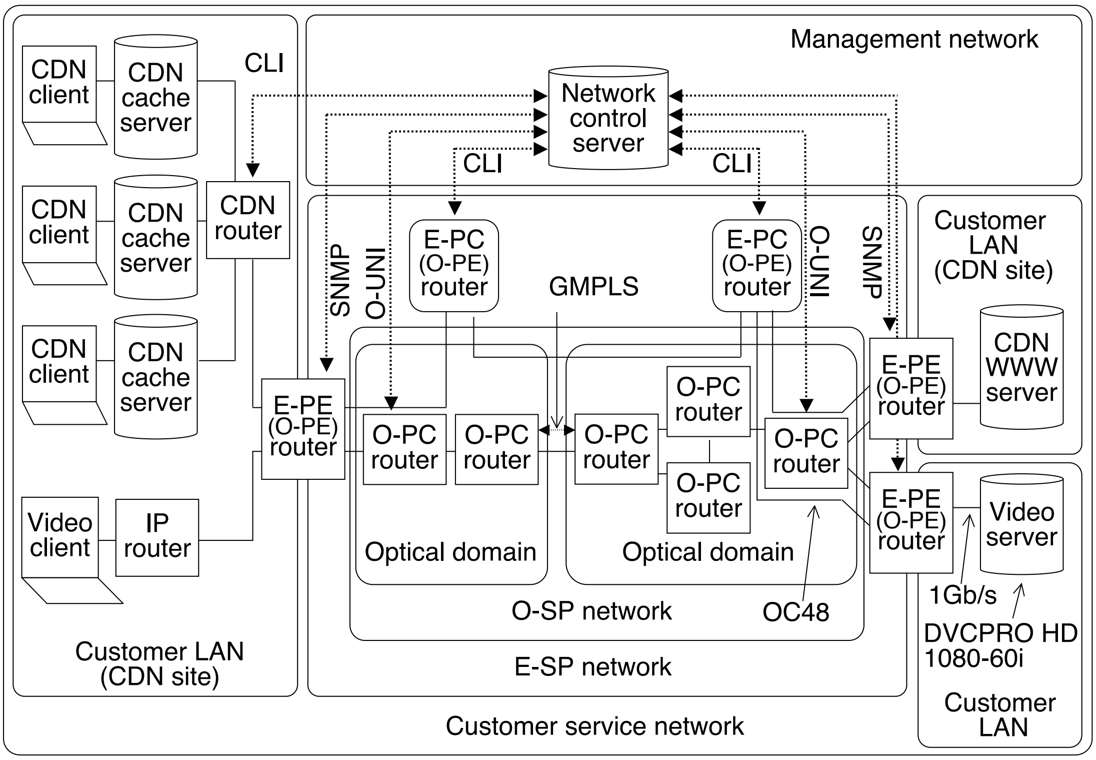

Figure 3.12: Experimental network configuration

(1) Traffic-driven path allocation

Background traffic (1 Gigabit per second) was loaded onto the left E-PC router shown in Fig.3.12 and then video traffic (100 Megabits per second) was carried from the video server towards the video client using hop-by-hop optical link (1 Gigabit per second) via the E-PC routers. Here, video communication quality was degraded because of the congestion. However, the NCS collected traffic information from the E-PC routers and detected the congestion at the output interface (1 Gigabit per second) of the left E-PC router. It then requested the O-PC routers to establish a cut-through optical path by means of the traffic-driven optical networking scheme and they established the path by means of the optical protection scheme. After the path had been established, video traffic (100 Megabits per second) was carried using the cut-through path (2.4 Gigabits per second) between E-PE routers and the video communication quality improved. Here, the control latency depends on a polling period (30 seconds) for the NCS to collect traffic information from the E-PC routers. Once the polling control had started, an optical path was established in 12 seconds.

(2) Path protection

The optical path that was carrying the video traffic, using the dedicated optical protection mechanism, was disconnected intentionally. However, with the protection mechanism, the path was switched to the backup path within 50 milliseconds and video communication quality was maintained without disturbance.

(3) Traffic localization

Background CDN traffic (10 accesses per second) was loaded onto some CDN cache servers and the CDN client requested some CDN content that was cached in these servers. Then, using the distributed content-caching mechanism, the CDN router forwarded the request to the CDN cache server that was not congested. The requested CDN contents (240 Megabits) were transferred to the CDN client within the LAN (1 Gigabit per second) and CDN data was soon displayed. Since traffic is localized within the site, video communication quality was maintained here.

(4) Application-driven path allocation

The CDN client requested some CDN content that was not cached in any CDN cache server and the CDN router requested the NCS to establish a cut-through optical path by means of the application-driven optical networking scheme. The optical path was established within 6 seconds and the requested CDN content (240 Megabits) was transferred using this path (2.4 Gigabits per second). Although the CDN content were displayed quickly, the quality of the video communication to the video client was degraded. This is because the existing traffic-driven optical path had blocked the requested application-driven path and it was removed by the prioritized path allocation scheme. As a result, the video traffic was then carried via the E-PC routers controlled by the electrical load-balancing mechanism. Here, video quality was degraded intentionally to show the proposed control visually. From the viewpoint of practical use, an optical path should be requested for the video communication and allocated as an application-driven path in order to maintain video quality.

(5) Path release

The CDN client finished receiving content and the CDN router requested the NCS to remove the path. Within 3 seconds, the requested optical path was removed. Then, the NCS collected traffic information and re-established a cut-through optical path for the video traffic. As a result, the video communication quality improved again after the traffic information polling period (30 seconds).

The results of these experiments show that the component mechanisms can be combined with each other to form a single network architecture and they can control an optical path dynamically, with a response time of the order of ten seconds. This signaling performance is almost the same as that of the conventional telephone networks.

3.6 Conclusion

Data communication networks that provision a best-effort service and a bandwidth-reserved service together are attractive to support various applications. Although an optical path network is attractive because of its broadband feature, bandwidth resource sharing between paths is difficult and throughput of the network may not be maintained effectively. In order to solve this problem, the multi-priority path allocation technology is effective. In this technology, best-effort service paths are first allocated as much as possible and then bandwidth-reserved service paths are allocated as demanded. In order to establish a requested bandwidth-reserved service path sufficiently, existing best-effort service paths that block the requested path are released. However, reachability toward all the destinations is still maintained because the rest traffic to be carried using the removed paths is carried by means of the electrical network. The results of the experiments using prototype systems have indicated that those two service networks can be combined with each other over the single provider network and they can control an optical path dynamically, with a response time of the order of ten seconds. As the result, the proposed technology improves the total throughput of the bandwidth-reserved service without excessive degradation of that of the best-effort service.

Chapter 4

Multi-policy path routing

In this chapter, a multi-policy path routing technology is proposed for provisioning heterogeneous services. This technology is designed to satisfy the different type of service policies such as low latency, high throughput and low cost. In an optical path network, a path routing algorithm determines service characteristics. However, no single conventional routing algorithm is able by itself to meet all these policies. In order to solve this problem, the proposed technology hybridizes multiple routing algorithms. In this technology, path setup requests are classified into multiple service classes according to their policy requirements and served by means of appropriate path routing algorithms. They are also assigned appropriate path priority levels for path replacing. According to the simulation results, the minimum-interference routing algorithm for the lowest priority, the widest shortest-path routing algorithm for the middle priority and the minimum-hop routing algorithm for the highest priority can provision a low-cost best-effort service, a fair-latency bandwidth-reserved service and a low-latency bandwidth-reserved service, respectively.

4.1 Introduction

Data communication networks have been used as the communication infrastructure and their service requirements are diversifying. In order to achieve broadband communications, the optical path technology is attractive. In an optical path network, a path routing algorithm is one of the important keys to differentiating service characteristics.

For example, the minimum-hop routing algorithm[40] achieves low-latency transmission, while network throughput may not be high because many requests tend to converge on a bottleneck link. On the other hand, the minimum interference routing algorithm[41] achieves high network throughput, while transmission latency may become large because longer bypass routes are used proactively for mitigating interference between paths. The widest shortest-path routing algorithm[42] balances transmission latency and network throughput.

Since no single conventional routing algorithm is able by itself to meet diversifying requirements, hybridization of multiple routing algorithms seems promising for provisioning multiple services. The simple solution is to divide an optical path network into multiple partitions and apply the different routing algorithm to each partition. However, this solution may increase service cost because network resources cannot be shared between the physical partitions.

In order to solve this problem, in this chapter, the multi-policy path routing technology is proposed. This technology hybridizes multiple routing algorithms using service classification and prioritized path allocation schemes. In this technology, path setup requests are classified into multiple service classes according to their policy requirements and served by means of appropriate path routing algorithms. In addition, they are assigned appropriate levels of path priority. When existing low-priority paths interfere with a new request to set up a high-priority path, the lower-priority paths are replaced with the higher-priority path to be established. Here, best-effort service paths are released even in the middle of the communications by means of loss-based path allocation scheduling, while bandwidth-reserved service paths are waited to be released by means of delay-based path allocation scheduling until the communications have been completed. The rest best-effort traffic to be carried using the released paths is carried by means of the electrical network in order to complete the communications.

According to the simulation results, the minimum-interference routing algorithm for the lowest priority, the widest shortest-path routing algorithm for the middle priority and the minimum-hop routing algorithm for the highest priority can provision a low-cost best-effort service, a fair-latency bandwidth-reserved service and a low-latency bandwidth-reserved service, respectively.

In this chapter, the reference network model is shown in Section 4.2 and the related technologies are summarized in Section 4.3. Then, the proposed technology is described in Section 4.4 and it is evaluated in Section 4.5. Finally, a brief conclusion is provided in Section 4.6.

4.2 Reference network model

The reference network model used to study the multi-policy path routing technology is shown in Fig.4.1. This model deploys the layering model and comprises an optical network layer, electrical network layer, customer-service network layer.

In the optical network layer, the optical service provider (O-SP) network is composed of optical provider core (O-PC) routers and optical provider edge (O-PE) routers. These are connected to each other using the Dense Wavelength Division Multiplexing (DWDM) links. Then, high-speed tunnels, called optical paths[6][11], are established between O-PE routers via O-PC routers. In the DWDM links, the number of multiplexed wavelengths and bandwidth of each wavelength correspond to the number of available optical paths and the path bandwidth, respectively. Every O-PC router does not convert wavelength of optical paths and thus each optical path comprises single-wavelength links.

In the electrical network layer, the electrical service provider (E-SP) network is composed of electrical provider core (E-PC) routers and electrical provider edge (E-PE) routers. Both these correspond to O-PE routers in the O-SP network and thus they are connected to each other using optical paths.

In the customer-service network layer, each E-PE router accommodates a number of local area networks (LANs) in customer sites. Customer-service networks such as VPNs that composed of distributed customer LANs lies over the E-SP network.

This model also deploys the control plane where a network control server (NCS) manages the multilayer network centrally.

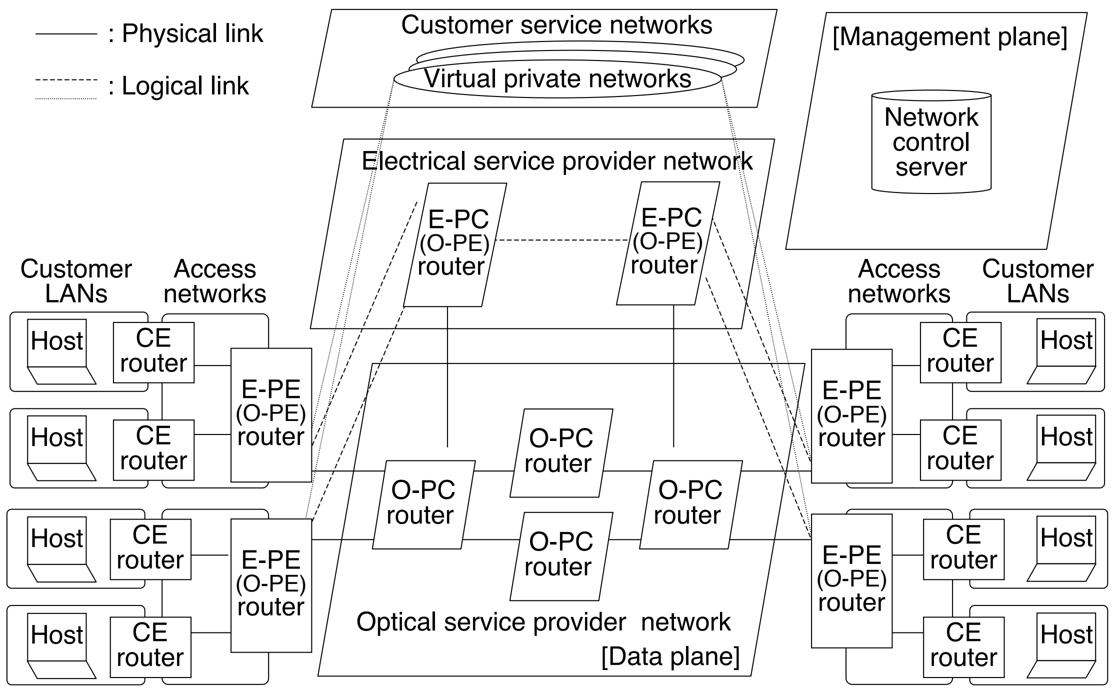

Figure 4.1: Reference network model for multi-policy path routing

4.3 Related technologies

In the multilayer networks, the amount of optical path resources is limited and thus cut-through optical paths should be allocated only for routes where a large amount of traffic is carried. This conventional technology[8] is depicted in Fig.4.2.

As a traffic engineering procedure, the NCS collects traffic information from EC routers. Then, it calculates traffic exchange patterns in the E-SP network. When it detects that a large amount of traffic is carried between two specific E-PE routers, it issues a request to set up a cut-through optical path between them. The NCS also collects traffic information periodically from the E-PE routers to monitor the amount of traffic carried along each optical path. When it detects that only a small amount of traffic is being carried via some path, it issues a request to remove that path.

Here path routes are determined by the NCS centrally[8][29] so as to allocate all paths optimally. Several routing algorithms have been proposed and evaluated from the viewpoint of throughput performance. Representative algorithms are the Minimum-Hop routing Algorithm (MHA)[40], the Widest Shortest-Path routing Algorithm (WSPA)[42] and the Minimum-Interference Routing Algorithm (MIRA)[41]. In the O-SP network without wavelength conversion, these algorithms should be applied to solve the Routing and Wavelength Assignment (RWA) problem[43] where each path should comprise single-wavelength links. No single conventional routing algorithm is capable of satisfying all the various requirements. The key features of these algorithms are described as following subsections.

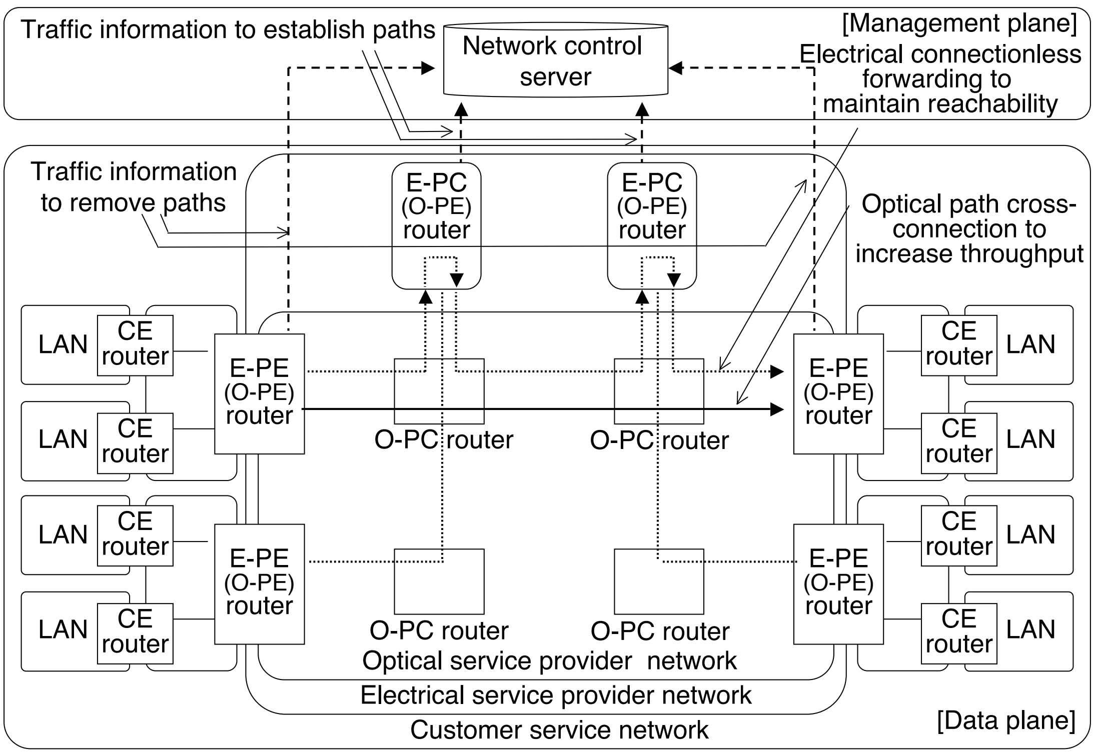

Figure 4.2: Conventional path allocation technology

4.3.1 Minimum-hop routing

The MHA[40] calculates the physical minimum-hop route. Due to the minimum-hop feature, the calculated routes consume only the minimum resources and transmission latency is also minimized. On the other hand, network throughput may become low when many requests converge on a bottleneck link causing interference, because, as shown in Fig.4.3, longer bypass routes are not used in this algorithm.

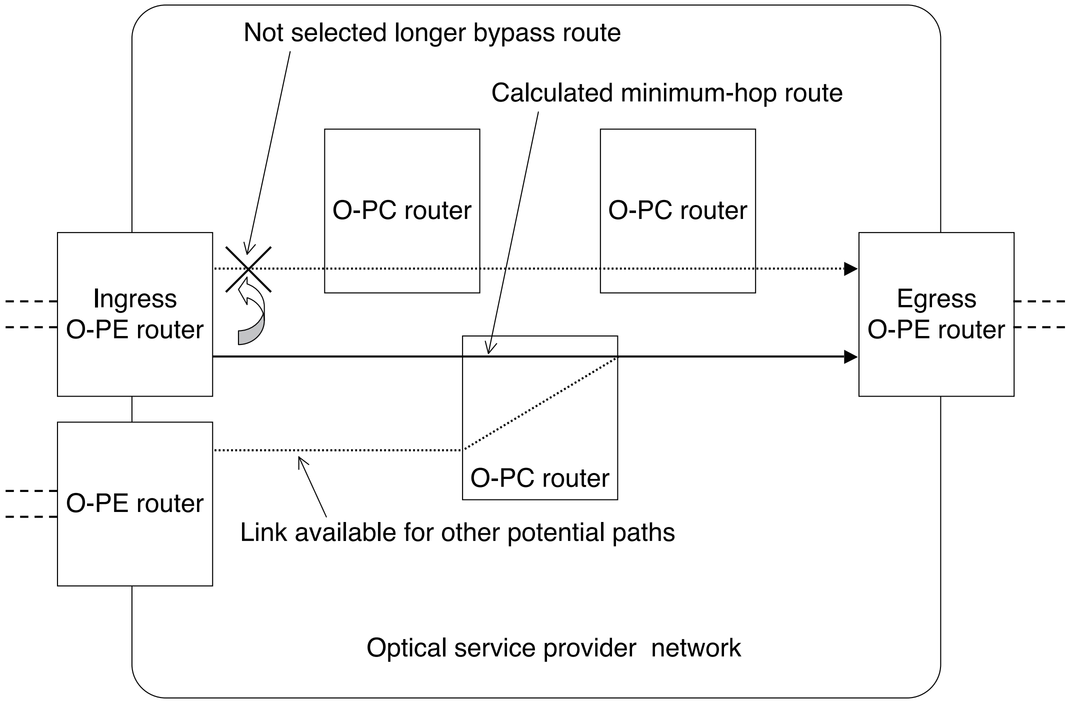

Figure 4.3: Minimum-hop routing algorithm (MHA)

4.3.2 Widest shortest-path routing

The WSPA[42] has been designed to improve the throughput characteristics of the MHA so as to use longer bypass routes when the minimum-hop route is filled with other paths. In this algorithm, when there are several alternative shortest paths, the one that has the highest currently available bandwidth is selected. Since bottleneck links can be bypassed as shown in Fig.4.4, traffic load may be balanced over the network. However, when many requests are still concentrated on the same link, network throughput is not increased effectively.

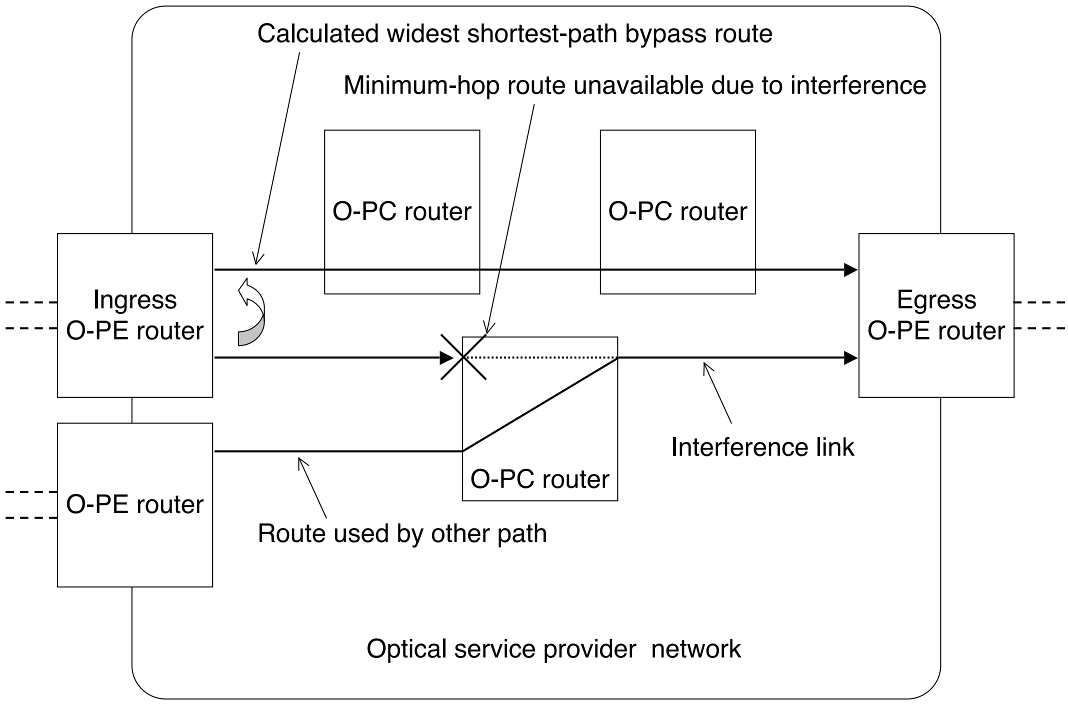

Figure 4.4: Widest shortest-path routing algorithm (WSPA)

4.3.3 Minimum-interference routing

The MIRA[41] has been designed to improve the throughput characteristics of the WSPA so that it can calculate the route that minimizes the probability of interference with other paths. As shown in Fig.4.5, this algorithm tries not to select a minimum-hop route, which probably interferes with other potential paths. Thus, even longer bypass routes are selected proactively for mitigating interference between links. Since with this approach a bottleneck link is not generated easily, network throughput can be improved efficiently. On the other hand, the route length may become longer and thus transmission latency may also become higher.

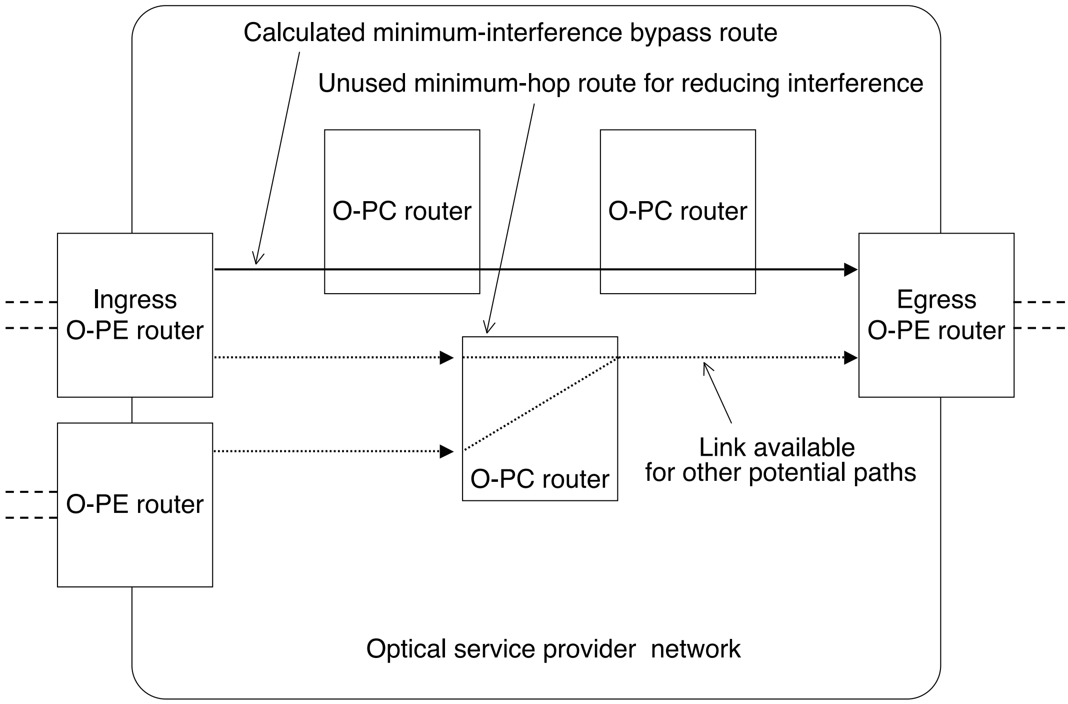

Figure 4.5: Minimum-interference routing algorithm (MIRA)

4.4 Multi-policy path routing technology

In this section, the multi-policy path routing technology is described. This technology is based on a service classification scheme, prioritized path allocation scheme and routing algorithm selection scheme described in Subsection 4.4.1, 4.4.2 and 4.4.3, respectively.

4.4.1 Service classification

In the proposed technology, a service classification scheme shown in Fig.4.6 is first introduced. In this procedure, path setup requests are classified into economy service (ES), basic service (BS), and premium service (PS) classes according to their policies. Features of these classes are as follows:

(1) Economy service class

The ES class is for cost-sensitive traffic and is served using best-effort packet forwarding. Optical paths of this class can be disconnected even in the middle of the communications. In order to complete such communications, the electrical network is also used. Most path setup requests issued by the NCS itself according to a traffic engineering procedure can be served effectively using this class.

(2) Basic service class

The BS class is designed to carry throughput-sensitive traffic and is served by way of bandwidth-reserved packet forwarding. Optical paths of this class are not disconnected until the communications using them have been completed. Bulk data transmission driven by applications such as video-on-demand can be served efficiently using this class.

(3) Premium service class

The PS class is designed to carry latency-sensitive traffic and is served by means of short route forwarding where bandwidth is also reserved along the routes. Realtime traffic generated by applications such as bi-directional video-communication and important business traffic in enterprise VPNs can be served effectively using this class.

For the policy control, all requests are concentrated on the NCS, which admits those different types of requests by taking account of the different objectives in order to achieve service differentiation and effective network resource utilization.

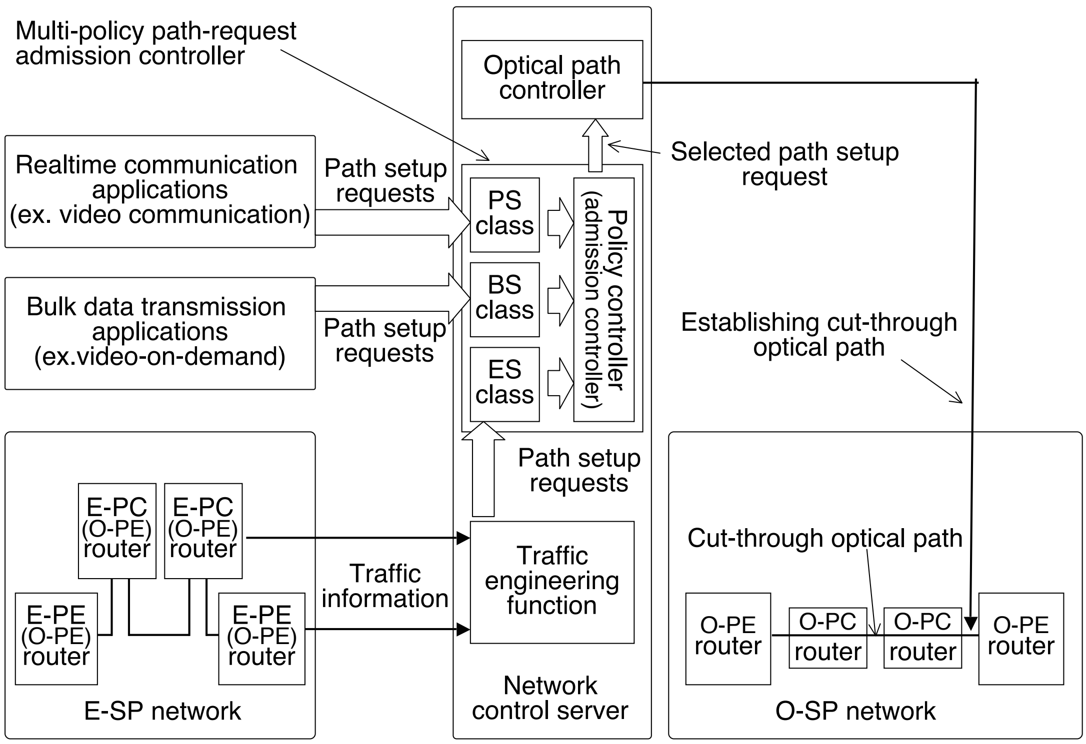

Figure 4.6: Service classification

4.4.2 Prioritized path allocation

In order to achieve stringent service differentiation, two types of prioritized path allocation mechanisms are then applied.

The first mechanism, shown in Fig.4.7, is based on a preemption mechanism[9][27] for PS-class and BS-class paths to replace ES-class paths. Normally, ES-class paths should be assigned wherever possible in order to maximize network throughput of the ES class. However, this means that the setup of newly requested PS-class or BS-class paths may be blocked by existing ES-class paths.

In order to solve this problem, the first mechanism disconnects such interfering ES-class paths even in the middle of the communications and replaces them with the BS-class or PS-class paths. The rest of traffic to be carried using the released paths is carried by means of the electrical network so that the communications can be completed. This mechanism is acceptable because the ES class offers only a best-effort data forwarding service.

The second mechanism is a pre-reservation mechanism for PS-class paths to acquire required path resources. The setup of newly requested PS-class paths may also be blocked by existing BS-class paths. However, such BS-class paths cannot be removed until the communications using them have been completed because they support a bandwidth-reserved data forwarding service.

In a typical operation, the mean path-holding period of BS-class paths should be shorter than that of PS-class paths according to their service objectives. Thus, in this mechanism, PS-class path requests are held until they can be served when such BS-class paths are removed on completion of the communications. During this waiting period, path resources are pre-reserved along the calculated route and thus other new paths cannot be assigned on this route. If the blocking BS-class paths are not removed within a specified period, those PS-class requests are rejected because of time out. Consequently, appropriate classification according to the mean path-holding period is important in implementing this scheme.

According to the first mechanism, the level of replacement priority for the PS and BS classes is higher than that for the ES class. Similarly, according to the second mechanism, the level of priority in pre-reservation for the PS class is higher than that for the BS and ES classes. As the result, in summary, the priority level in path allocation is highest for the PS class, followed by the BS class and finally the ES class.

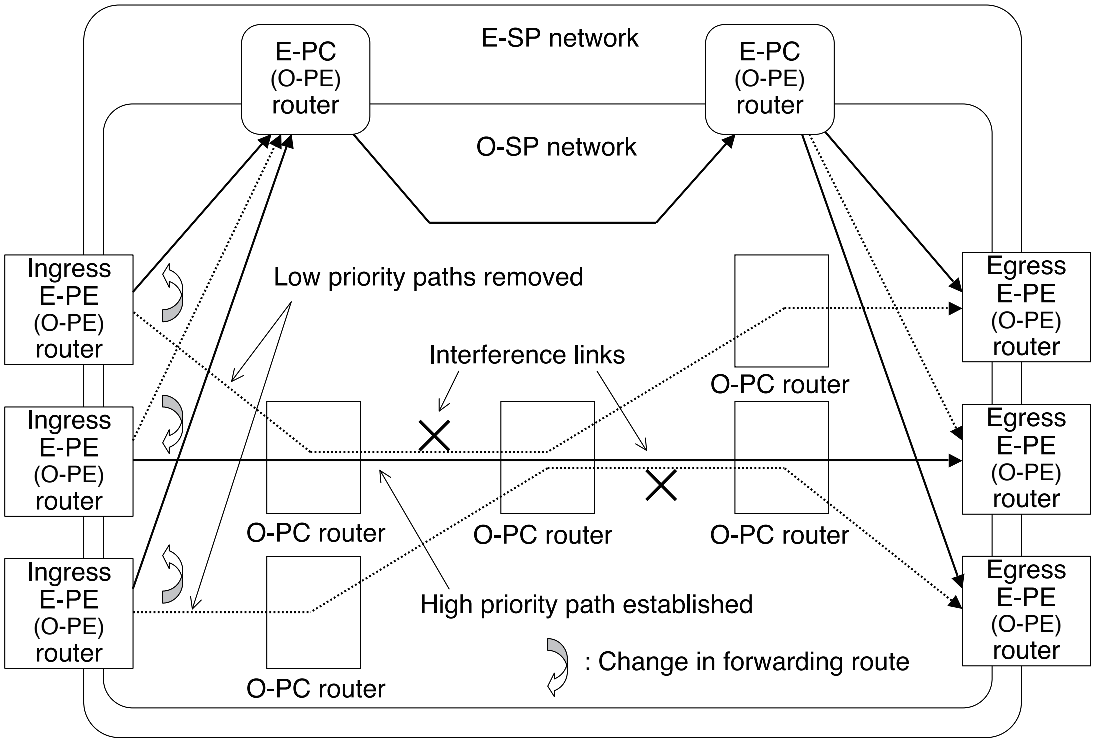

Figure 4.7: Prioritized path allocation

4.4.3 Routing algorithm selection

In order to satisfy various requirements, multiple routing algorithms are finally hybridized, as shown in Fig.4.8. This algorithm is call a hybrid path routing algorithm (HRA). In a typical design of the HRA, the MHA, WSPA and MIRA are assigned to the PS, BS and ES classes, respectively. These classes are finally integrated into the physical plane by means of the prioritized path allocation scheme.

The PS class requires low-latency bandwidth-reserved transmission and thus the MHA is appropriate for this class. However, only a small number of PS-class requests can be admitted. The BS class allows fair-latency transmission, so a large number of BS-class requests can be served to increase network throughput. Accordingly, the WSPA, rather than the MHA, is suitable for this class. Finally the ES class requires low-cost transmission and allows high latency, and so the MIRA is effective for this class.

In order to solve the RWA problem[43], these routing algorithms are applied so that the O-SP network comprises single-wavelength planes and path routes are calculated not to across those planes.

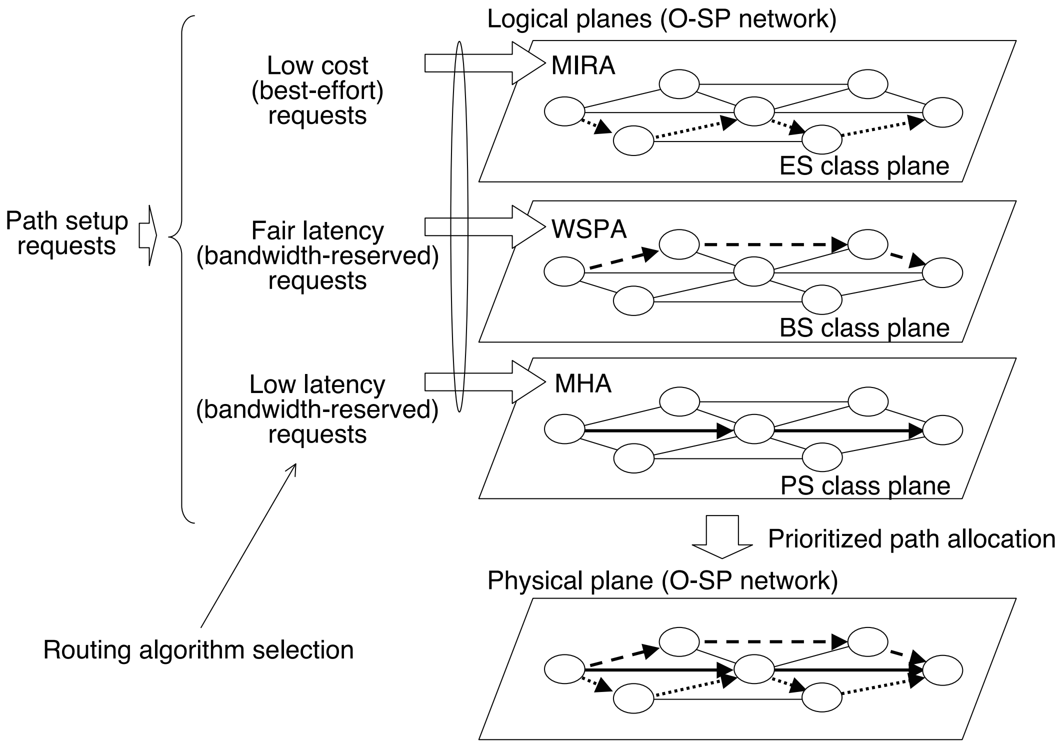

Figure 4.8: Routing algorithm selection

4.5 Evaluations and discussions

In this section, the path routing technologies are evaluated. The simulation models for the evaluation are depicted in Subsection 4.5.1. Then the simulation results for the total throughput, per-class throughput and per-class latency are described in Subsection 4.5.2, 4.5.3 and 4.5.4, respectively.

4.5.1 Simulation models

The throughput and latency characteristics of multilayer networks depend on the network topologies. Then two simulation models shown in Fig.4.9 and 4.10 were deployed to simulate the multilayer network model shown in Fig.4.1. The former simulates a network model where only small number of bypass routes can be allocated and is called “the sparse model”. The latter simulates a network model where a large number of bypass routes can be allocated and is called “the dense model”. The latter has been evaluated widely in the literature[41][44][45].

In these figures, symbols I and E represent ingress and egress E-PE routers, respectively. Thus, nodes 0, 3, 7, 8 and 12 are E-PE routers. Nodes A and B are E-PC routers to simulate the E-SP network. Other nodes are O-PC routers to simulate the O-SP network. Unidirectional and bidirectional arrows represent unidirectional and bidirectional links, respectively.

The simulation conditions were as follows: In Fig.4.9 and 4.10, six wavelengths and one wavelength were multiplexed into the thick and thin arrows, respectively. The normalized path bandwidth was 20 units of volume per step of time. Thus, the thick and thin arrows represent normalized bandwidth of 120 and 20 units per step, respectively. The normalized propagation latency of each link was a period of 1 step.

Under these conditions, path setup requests were issued at random intervals, conforming to an exponential distribution, for each of the paths between an ingress and an egress E-PE(O-PE) routers. The probabilities of issuing requests of PS-class, BS-class and ES-class were in the ratio 1:10:100. The normalized path-holding periods for PS-class, BS-class and ES-class paths were 100, 30 and 10 steps, respectively. The total traffic load was calculated as the mean total requested bandwidth for all classes. Each normalized simulation period was 2000 steps.

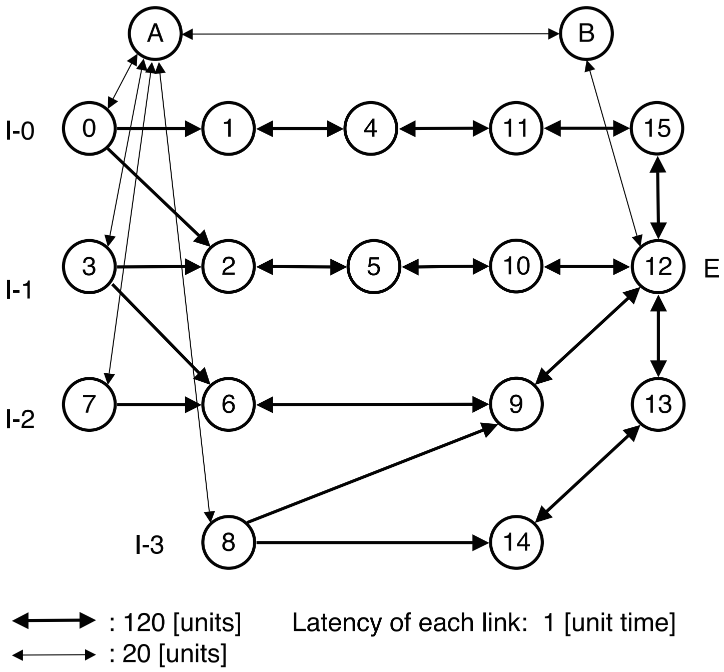

Figure 4.9: Sparse model for simulation

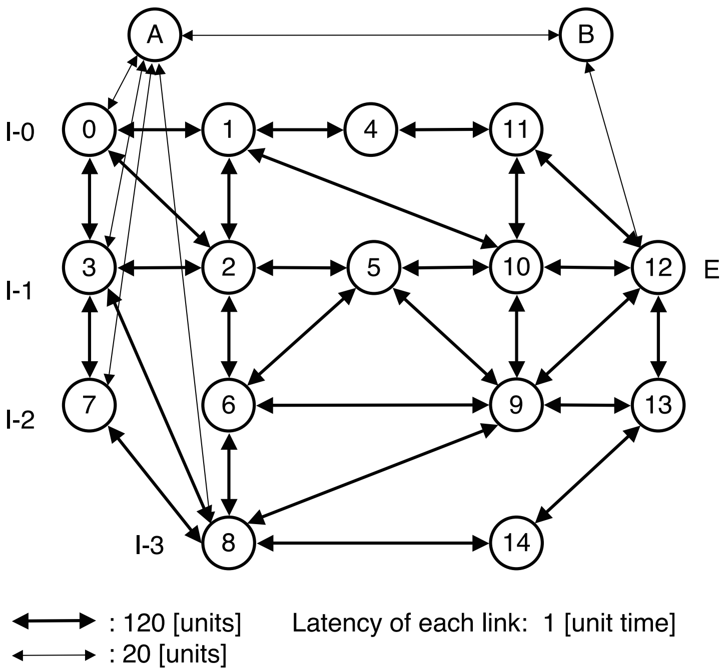

Figure 4.10: Dense model for simulation

4.5.2 Total throughput

The total throughput was first evaluated. This is the most important factor in order to characterize the whole network performance. In this simulation, it depended on a routing algorithm when the prioritized path allocation scheme was applied. The simulation results for the sparse and dense models are shown in Fig.4.11 and 4.12, respectively. In these figures, the vertical and horizontal axes show the total throughput and the total traffic load, respectively.

The total throughput decreased from the algorithm showing the highest throughput in the order HRA, MIRA, WSPA and MHA for the sparse model, as shown in Fig.4.11, but in the order HRA, WSPA, MIRA and MHA for the dense model, as shown in Fig.4.12. The total throughput of the HRA was in each case the highest. This reason is discussed in Subsection 4.5.3.

In the simulation, the total throughput also depended on the prioritized path allocation scheme. The simulation results for the sparse and dense models are shown in Fig.4.13 and 4.14, respectively. In these figures, the vertical and horizontal axes show the total throughput and the total traffic load, respectively. In addition, the designation "PPA:on" and "PPA:off" indicate that the prioritized path allocation scheme is applied and that it is not applied, respectively. The HRA was applied to each of these simulations.

The results showed that the prioritized path allocation mechanism did not necessarily increase the real total throughput. The figures show that it was in fact reduced in the maximum by about ten percent. However, this scheme is still important from the viewpoint of commercial business where the service prices of the BS and PS classes are higher than that of the ES class on account of their additional business value. The real total throughput was therefore recalculated using appropriate price weights and defined this as the effective total throughput.

Typically, a service price is weighted almost in proportion to the amount of reserved bandwidth. In the conservative estimation, which is only one example, the service price of the BS and PS classes were weighted at three times and five times that of the ES class, respectively.

Then, the effective total throughput was calculated as gains per step. The results are also shown in Fig.4.13 and 4.14. In these figures, the prioritized path allocation scheme increase the effective total throughput in the maximum by about twenty percent.

Although lower-weighted pricing seems more attractive for customers, it should be at least determined and evaluated so as to increase the effective total throughput for service providers. The reason of the real throughput degradation is also discussed in Subsection 4.5.3.

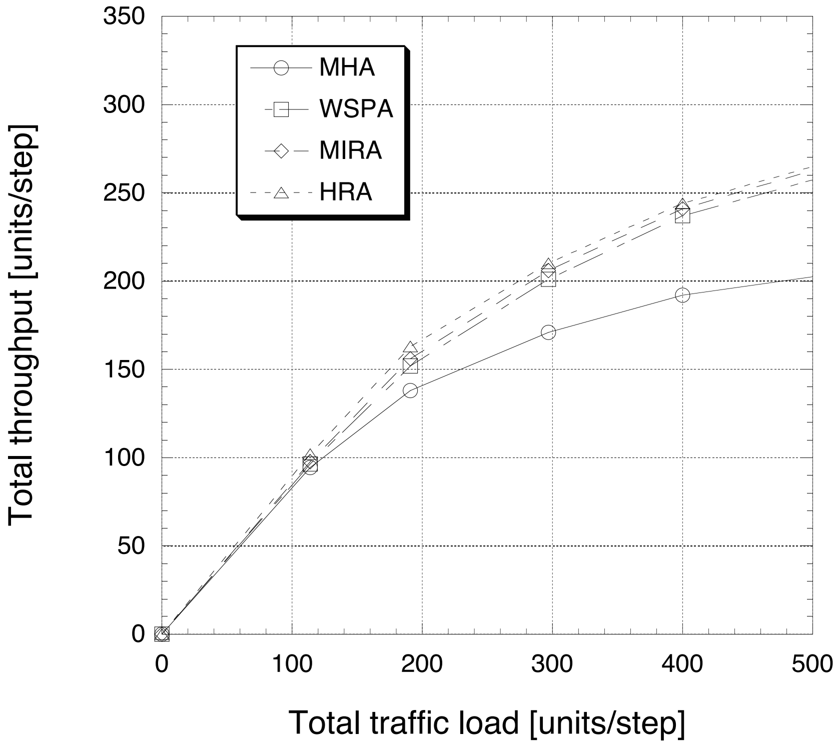

Figure 4.11: Total throughput for the sparse model

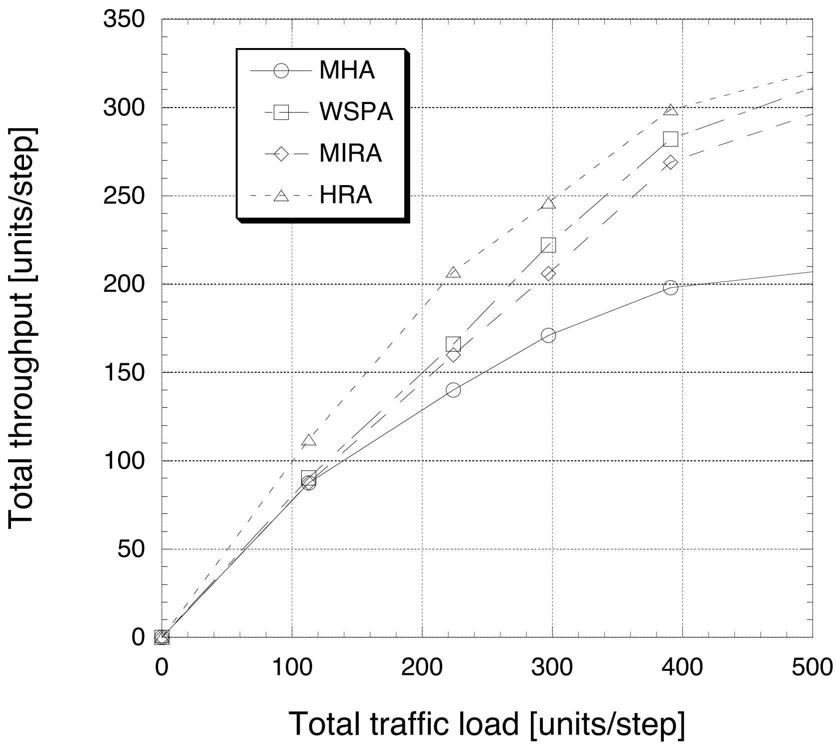

Figure 4.12: Total throughput for the dense model

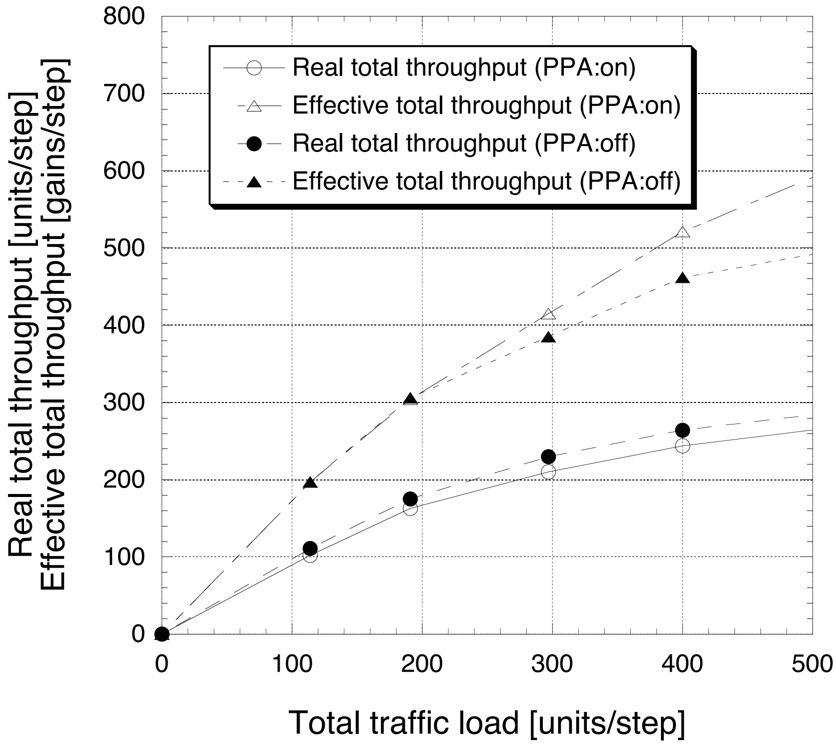

Figure 4.13: Total throughput of HRA paths for the sparse model

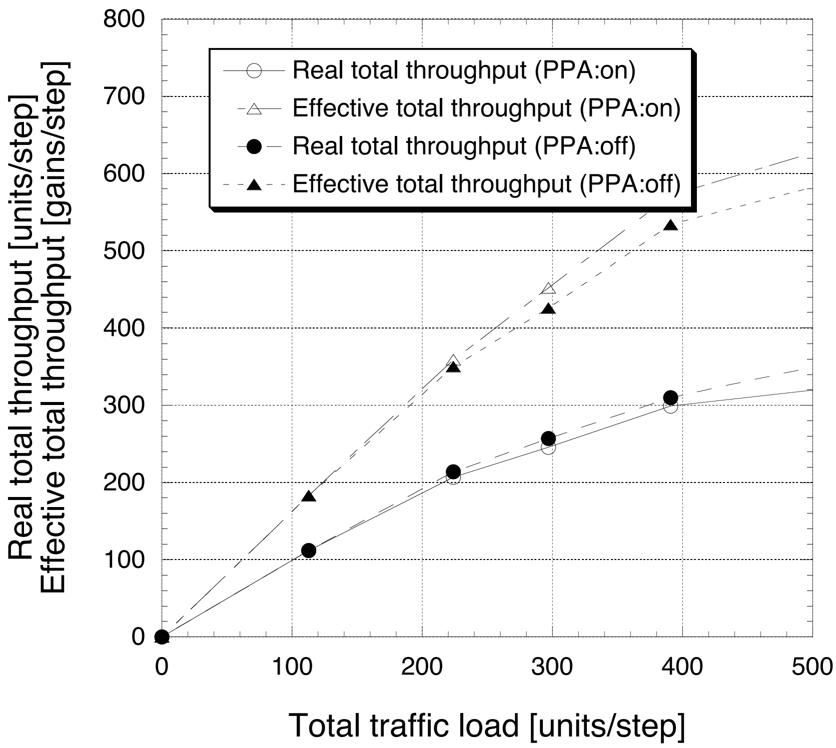

Figure 4.14: Total throughput of HRA paths for the dense model

4.5.3 Per-class throughput

The per-class throughput was then evaluated in order to analyze the total throughput characteristics. The simulation results of routing algorithm dependency with the sparse and dense models are shown in Fig.4.15 and 4.16, respectively. In these figures, the vertical and horizontal axes show the per-class throughput and the total traffic load, respectively. The simulation conditions were the same as those used to obtain Fig.4.11 and 4.12.

In the sparse model, the ES-class throughput decreased from the algorithm showing the highest throughput in the order HRA, MIRA, WSPA and MHA, as shown in Fig.4.15. Then, the minimum interference feature of the MIRA appears to be effective and similarly the HRA, in which the MIRA is applied to the ES class, also seems effective.

On the other hand, in the dense model, the ES-class throughput decreased in the order HRA, WSPA, MIRA and MHA, as shown in Fig.4.16. In this model, the WSPA seems more effective than the MIRA for the ES class. However, the HRA, in which the MIRA is applied to the ES class, is more effective than the WSPA. Then, the WSPA for the BS class is the important key to improving throughput. This is because a BS-class path might be established so as to disconnect multiple interfering ES-class paths.

The number of disconnected ES-class paths by a shorter BS-class WSPA path would be smaller than that by a longer BS-class MIRA path. Thus, the per-class throughput of the ES-class achieved with the BS-class WSPA would be higher than that achieved with the BS-class MIRA.

The per-class throughputs of the BS and PS classes did not depend on the path routing algorithm used. This is because the per-class traffic loads of the BS and PS classes were suppressed to be small for achieving appropriate operation.

As the consequence, the MIRA for the lowest-priority ES class and the WSPA for the middle-priority BS class seem effective in increasing the number of ES-class paths allocated and in decreasing the number of ES-class paths removed, respectively. For a similar reason as for the BS class, the minimum-hop feature of the MHA applied to the highest-priority PS class also seems effective.

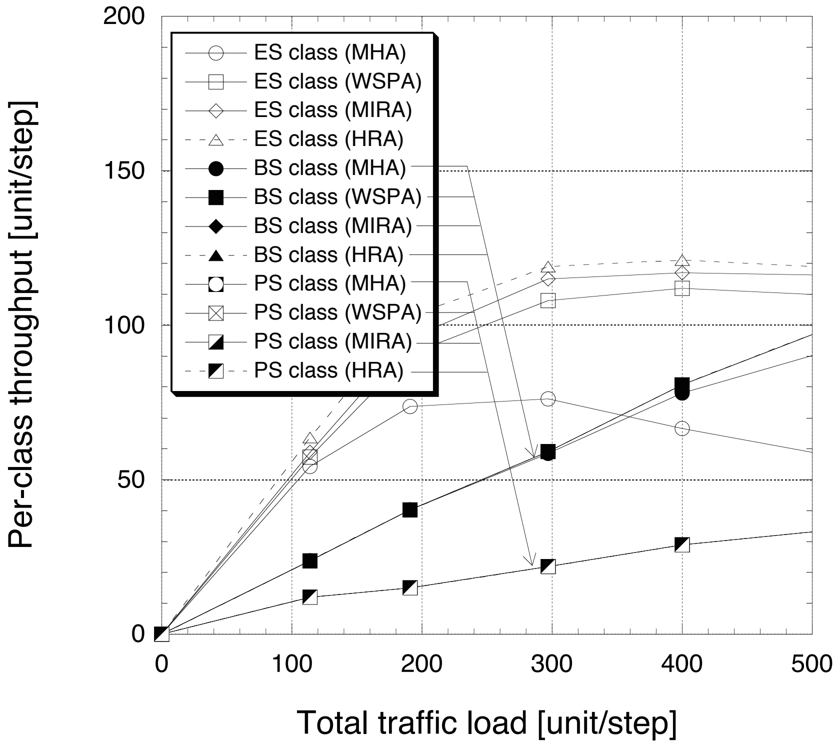

Figure 4.15: Per-class throughput for the sparse model

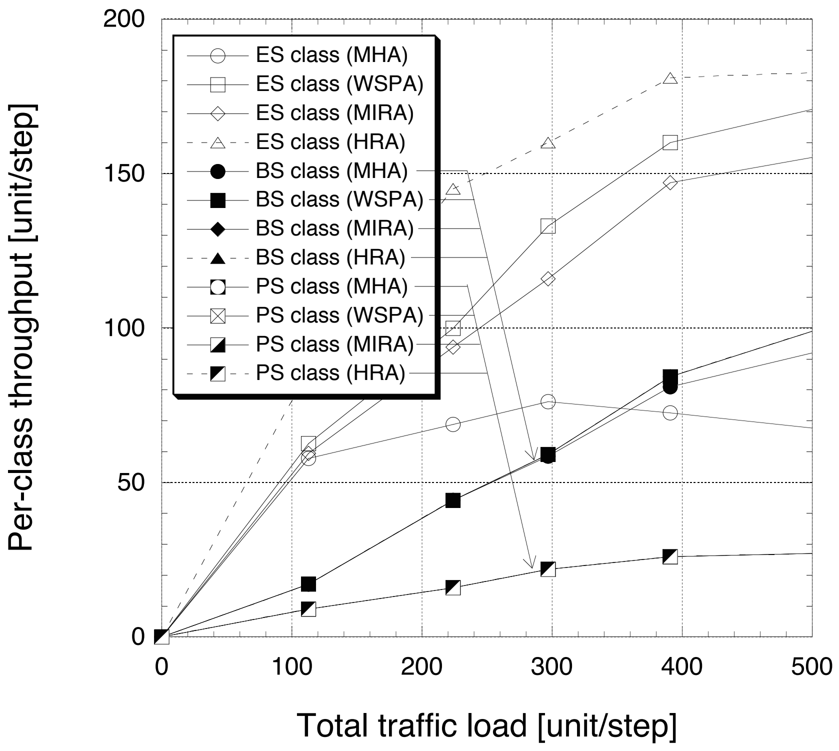

Figure 4.16: Per-class throughput for the dense model

In the simulation, the per-class throughput also depended on the prioritized path allocation scheme. The simulation result for the sparse and dense models are shown in Fig.4.17 and 4.18, respectively. In these figures, the vertical and horizontal axes show the per-class throughput and the total traffic load, respectively. In addition, the designation "PPA:on" and "PPA:off" indicate that the prioritized path allocation scheme is applied and that it is not applied, respectively. The simulation conditions were the same as those used to obtain Fig.4.13 and 4.14.

The per-class throughput was highest for the ES class, followed by the BS class and then the PS class, according to the traffic load simulation conditions, which seemed appropriate from the viewpoint of network operation.

The throughput of the high-priority PS and middle-priority BS classes were increased in the maximum by about forty percent by means of the prioritized path allocation scheme. On the other hand, the throughput of the low-priority ES class decreased, also in the maximum by about forty percent.

Since a BS-class path might be established so as to disconnect multiple interfering ES-class paths, the real total throughput would be decreased. However, the prioritized path allocation scheme is effective to increase throughput of the valuable BS and PS classes. Then it would be finally increases the effective total throughput, as described in Section 4.5.2.

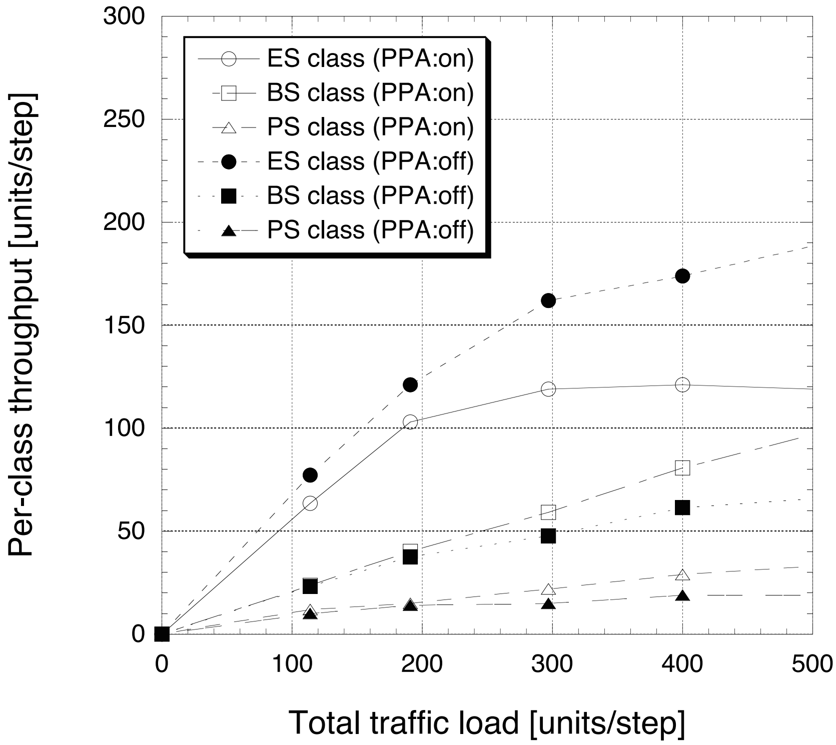

Figure 4.17: Per-class throughput of HRA paths for the sparse model

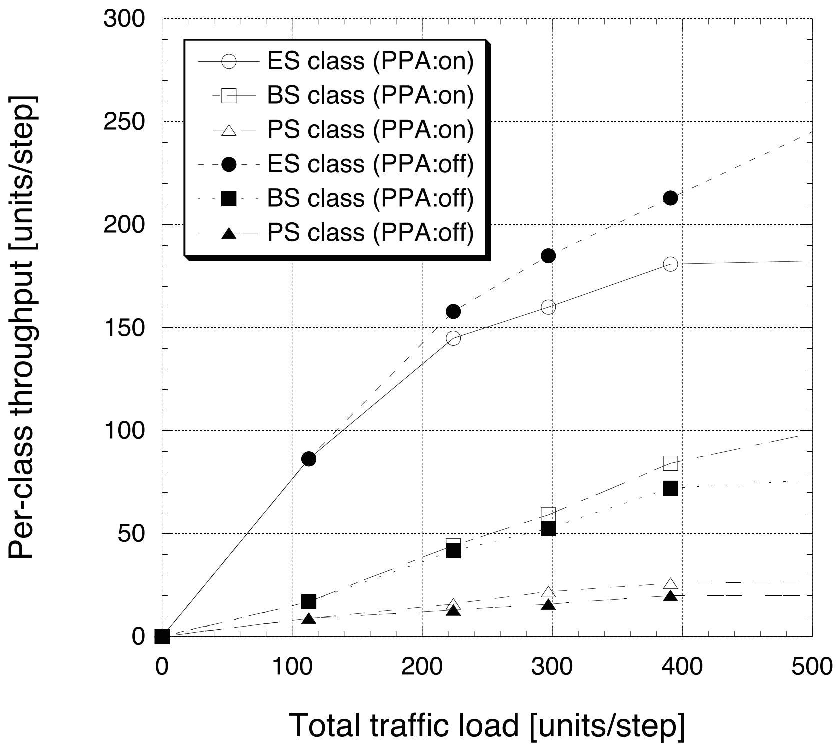

Figure 4.18: Per-class throughput of HRA paths for the dense model

4.5.4 Per-class Latency

The per-class latency was finally evaluated. In the simulation, the latency was calculated as the number of hops along a path route and it depended on a path routing algorithm. Here the prioritized path allocation scheme was always applied. The simulation results for the sparse and dense models are shown in Fig.4.19 and 4.20, respectively. In these figures, the vertical and horizontal axes show latency and types of routing algorithms, respectively. The traffic load was about 400 units per step.

In the results, latency was highest for MIRA, followed by WSPA and then MHA. This is because MIRA selects longer bypass routes to benefit all future path setup requests and thus even for the high-priority PS class, the latency was still higher than for the other algorithms. In contrast, WSPA and MHA select shorter routes, only considering the route that seems best for the request itself. Thus, the latency for the high-priority PS and middle-priority BS classes was lower. The differences between the algorithms in the dense model were larger than those in the sparse model because longer bypass routes came to be selected in the dense model.

In the case of HRA, the latency for the ES, BS and PS classes were almost the same as the ES, BS and PS classes using MIRA, WSPA and MHA, respectively. Since the PS class was the highest priority class, the latency of the PS class in the HRA was about the same as that in the original (non-hybridized) MHA. Similarly, the latency of the BS class in the HRA was almost the same as that in the original WSPA. For the dense model, the latency of the PS class was almost half of that of the ES class.

Consequently, HRA can successfully support both the low-latency feature of MHA for the PS class and the fair-latency feature of WSPA for the BS class. This feature is important in offering latency-differentiated services.

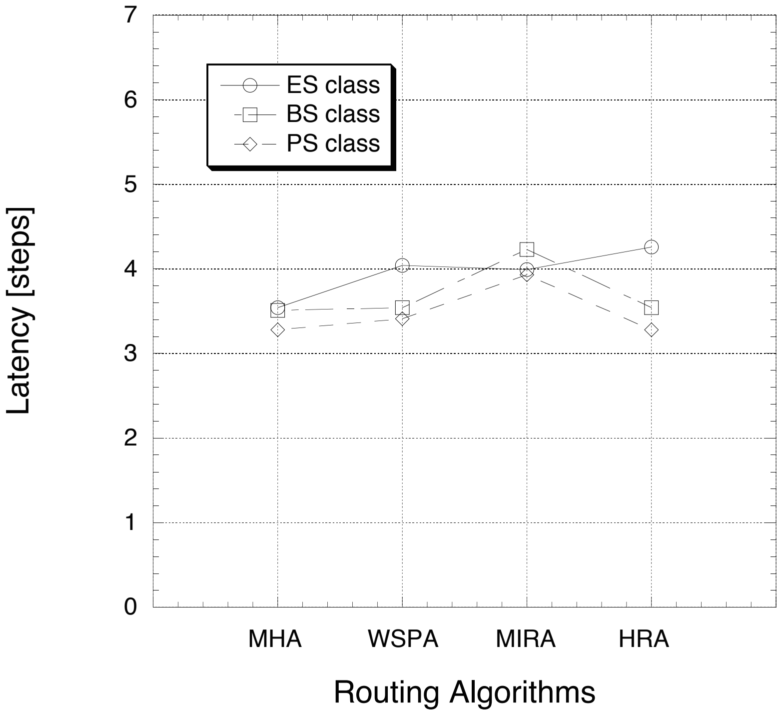

Figure 4.19: Per-class latency for the sparse model

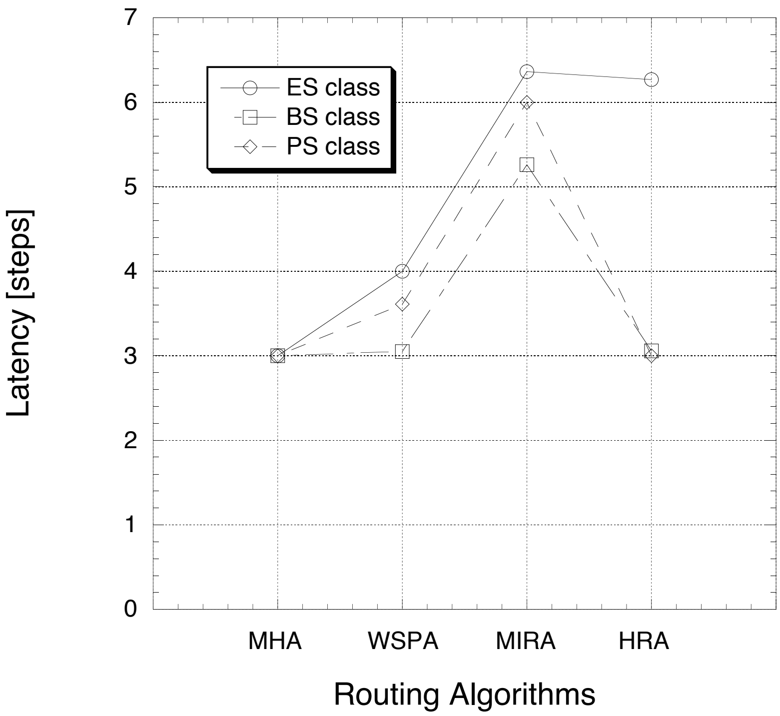

Figure 4.20: Per-class latency for the dense model

4.6 Conclusion

Data communication networks are required to provision multiple services efficiently. In an optical path network, a path routing algorithm can differentiate service characteristics. However, no single conventional routing algorithm is able by itself to meet diversifying requirements. In order to solve this problem, the multi-policy path routing technology is effective. In this technology, a path setup request is classified into multiple service classes according to its policy requirement and served by means of the appropriate path routing algorithm. Bandwidth resources are shared between these classes by means of the prioritized path allocation scheme. When a best-effort service path is released in the middle of the communication, the rest traffic to be carried using the released paths is carried by the electrical network. On the other hand, a bandwidth-reserved service path is not released and waited until the communication has been completed. In the results of the computer simulations, the latency of the minimum-hop routed paths can be decreased to be almost half of that of the minimum-interference routed paths. Moreover, the throughput of the high-priority paths was increased in the maximum by about forty percent, while that of low-priority paths was decreased in the maximum by about forty percent. Consequently, this technology is applicable to provision a low-cost best-effort service, a fair-latency bandwidth-reserved service and a low-latency bandwidth-reserved service by means of the minimum-interference routing algorithm for the lowest priority, the widest shortest-path routing algorithm for the middle priority and the minimum-hop routing algorithm for the highest priority. As the result, the proposed technology is useful for provisioning heterogeneous services effectively.

Chapter 5

Conclusions

In this thesis, the multilayer networking architecture has been proposed for data communication networks to satisfy the requirements of heterogeneous service provisioning.

The multilayer networking architecture designed in Chapter 1 deploys the network hybridization approach. This approach is effective because most conventional networks have been designed for a specific service. However, the open problems of transfer network selection, bandwidth resource utilization and multi-service provisioning should be solved. Thus, as the solutions for those problems, the proposed architecture has been designed based on the multilayer data forwarding technology, the multi-priority path allocation technology and the multi-policy path routing technology.

The multilayer data forwarding technology proposed in Chapter 2 is available to solve the problem of transfer network selection by means of the cut-through optical path allocation according to the flow amount. In this technology, the electrical connectionless network maintains reachability towards many destinations effectively and the optical path network improves throughput between a specific pair of cites using cut-through optical paths. In order to maintain throughput against fluctuations of traffic patterns and routing information, the lightweight processing approach, which is composed of the overlay networking and the electrical cut-through control, is also deployed. The results of the mathematical analysis have shown that the number of optical paths in the network can be adjusted according to traffic demand because of the optical cut-through control. In addition, due to the overlay networking, the number of optical path signaling routes to be handled by each core router can be reduced to be the same as that of edge routers in the network. Furthermore, owing to the electrical cut-through control, the number of packet forwarding routes to be handled by each edge router can be reduced to be the same as that of accommodated customers by that router. On the other hand, in the peer-based basic approach, both numbers are almost the same as that of the Internet full routes. Accordingly, this technology enables a large-scale network to provision a best-effort data forwarding service efficiently.

The multi-priority path allocation technology proposed in Chapter 3 is effective for solving the problem of bandwidth resource utilization by means of the bandwidth resource sharing approach. In this technology, a bandwidth-reserved service network and a best-effort service network are hybridized with each other using the loss-based path allocation scheduling. Although this scheduling may release optical paths for the best-effort service, the rest of traffic to be carried using released paths is carried by way of the electrical network. The results of the experiments using prototype systems have indicated that those two service networks can be combined with each other over the single provider network and they can control an optical path dynamically, with a response time of the order of ten seconds. Therefore, this technology is feasible and effective to provision a best-effort service and a bandwidth-reserved service simultaneously.

The multi-policy path routing technology proposed in Chapter 4 is promising to solve the problem of multi-service provisioning by means of the heterogeneous service provisioning approach. In this technology, service networks are characterized using the different types of path routing algorithms. In addition, even bandwidth-reserved service networks can be hybridized with each other by way of the delay-based path allocation scheduling. In the results of the computer simulations, the latency of the minimum-hop routed paths was decreased to be almost half of that of the minimum-interference routed paths. Moreover, the throughput of the high-priority paths was increased in the maximum by about forty percent, while that of low-priority paths was decreased in the maximum by about forty percent. Consequently, this technology is applicable to provision a low-cost best-effort service, a fair-latency bandwidth-reserved service and a low-latency bandwidth-reserved service by means of the minimum-interference routing algorithm for the lowest priority, the widest shortest-path routing algorithm for the middle priority and the minimum-hop routing algorithm for the highest priority.

Those three technologies cover fundamental network hybridization patterns and thus the proposed multilayer networking architecture achieves wide applicability for provisioning heterogeneous communication services. As the conclusion, the proposed architecture is suitable for the multimedia data communication infrastructure.

In future works, according to the network hybridization approach, the proposed architecture will be extended so as to strengthen multi-service capability. Specifically, it will be further hybridized with the VPN provisioning architectures to provide heterogeneous virtual networking services for cloud computing systems.

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