Traffic Engineering Techniques in Photonic Networks

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Abstract

A photonic network offers a high-speed circuit with wavelength division multiplexing (WDM) transmission and wavelength routing. In current WDM transmission technology, the number of wavelengths that can be accommodated in one optical fiber is less than about one hundred due to physical restrictions. Since wavelength is a comparatively valuable resource, it should be used efficiently in the photonic network. To offer new network services, it is necessary to control optical paths dynamically. This paper describes optical path control techniques and newly proposed variable-capacity optical path techniques, which are both provided by signaling protocols based on generalized multiprotocol label switching (GMPLS).

1. Introduction

With broadband services becoming popular, communication service providers must now offer high-speed and wide-bandwidth circuits such as 2.5 or 10 Gbit/s as quickly as possible. To raise circuit capacity, there have been many research and development efforts resulting in technologies such as wavelength division multiplexing (WDM) and wavelength routing of high-volume paths, which are called optical paths or wavelength paths[*1], using optical cross-connect (OXC) switches. A photonic network is defined as a simple and scalable optical network based on a new paradigm characterized by functions that make it possible to add/drop any wavelengths at any nodes on the optical path route and to route the optical path signal without converting it into an electrical signal, as well as functions that support a high transmission capacity by using WDM [1]. In current WDM transmission technology, the number of wavelengths that can be accommodated into one optical fiber is less than one hundred due to physical restrictions. Therefore, we must regard wavelength as a comparatively valuable resource in the network and use it as efficiently as possible.

Along with the progress in optical transmission achieved by the photonic network, an environment to provide high-capacity circuits at a low cost has been arranged. We assume that such high-capacity circuits are used for transmitting data traffic, so a traffic control technology to handle data traffic effectively within the transport network is very important. IP traffic is thought to account for most of today's broadband traffic and its characteristics differ greatly from those of conventional telephony traffic. For example, with IP traffic, the amount of traffic has little dependence on distance, the variation in traffic patterns is very large, and a lot of traffic is bursty.

In the conventional hierarchical network that creates high-volume flows by converging local traffic, there are some drawbacks in that traffic is concentrated onto the central node which converges the traffic, and a considerable imbalance is generated in usage efficiency of network facilities depending on traffic conditions. To address such problems, research and development of a mesh-type photonic network that is less dependent on traffic conditions and allows flexi-

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*1 Optical path: A path for transmitting information end-to-end using one wavelength. The transmission rate is 2.5, 10, or 40 Gbit/s. At present, several paths of different wavelengths are multiplexed by WDM onto one optical fiber. In the future, multiplexing is expected to be performed by optical time division multiplexing (OTDM) or optical code division multiplexing (OCDM).

ble network expansion has been accelerated. By introducing a mesh-type network structure, it should be possible to make traffic flows uniform through load distribution, respond quickly to needs to scale up the network, and easily track changes in traffic volume.

By utilizing the mesh-type photonic network, it is possible to create new network services such as i) direct wavelength connections between data centers, ii) on-demand (i.e., one-click) provision, high-capacity paths independent of upper-layer services, and iii) wavelength-level virtual private network services. These new network services require traffic engineering to control high-capacity paths (typified by a wavelength path) so as to provide a virtual ultrahigh-capacity path by bundling multiple wavelength paths, or controlling a high-capacity path to respond quickly to a user's request for setting-up or releasing the path, or allowing the network to provide a circuit actively by aggregating unused bandwidth.

So far, in NTT Network Innovation Laboratories, we have carried out experimental research on these new network services by constructing a photonic network using a centrally controlled network management system (NMS). Since central control focuses on effectively operating network resources (typified by wavelength), it is difficult to address the requirement to control high-capacity paths rapidly.

For this purpose, a traffic engineering technique based on a distributed control scheme is useful. To control high-capacity paths in a distributed manner, the concepts of multiprotocol label switching (MPLS[*2]) [2] and generalized MPLS (GMPLS) have been proposed [3], and research and development have been accelerated, with the aim of controlling high-capacity paths utilizing a signaling protocol for setting up a label switched path (LSP), which is a logical path used in MPLS. In addition, in a photonic IP network composed of the combination of an IP network and a photonic network, a HIKARI router (photonic MPLS router) [4], [5] enables seamless and integrated control of IP/MPLS/photonic MPLS (i.e., GMPLS) aiming to achieve efficient resource management of IP (MPLS) networks and a photonic network.

In this paper, after a brief overview of traffic engineering technology in the photonic network, we discuss wavelength path control technology in the photonic network, ultrahigh-capacity and variable-capacity path control technology, and the multi-layer traffic control technology in the HIKARI router.

2. Traffic engineering technology

Traffic engineering aims to effectively utilize network resources such as bandwidth by arbitrarily controlling the traffic. In a photonic network, it can be defined as a technique for setting optimum wavelength paths so as to provide wavelength resources at any time and in any amount as required. To set up a wavelength path, it is necessary to solve two problems—selecting the path route and allocating the wavelength—at the same time. The difficulty of finding the solution depends on i) the network topology (point-to-point, ring, or mesh), ii) whether or not network recovery from failure is considered, and iii) whether working and backup paths are required and up to which layer optimization is considered, that is, whether optimization is executed only at the wavelength layer or in multiple layers including the upper and lower layers.

Furthermore, different approaches can be taken to optimize the wavelength path: i) taking enough time based on enough information in a manner similar to centralized control or ii) performing quasi-optimization by making an instant judgment in a manner like distributed control. The applicability of both approaches depends on the time available to solve the problems and the duration of the wavelength path setup/release intervals and also depends on whether the wavelength path is a semi-permanent path or a temporary path with a short holding time like a switched virtual circuit. When a quasi-optimization method is used, there is also an approach that aims to utilize resources more effectively by re-allocating the path with an appropriate timing.

Figure 1 shows traffic engineering technology mapped in three dimensions against axes showing the complexity of network topology, dynamics of wavelength paths, and number of layers, as described above. The closer to the origin of each axis, the more difficult the problem is to solve. In this paper, we discuss high-speed wavelength path setup technology in a single layer in section 4.2, variable-capacity wavelength path technology based on cooperation between layers in section 4.3, and path setup technology that

*2 MPLS: Multiprotocol label switching transmits information by attaching a fixed-length label to each IP packet used in the IP network. MPLS was extended and developed toward the lower layer as generalized MPLS (GMPLS). In GMPLS, when wavelength information is attached to a bit-stream as a label it is called MPλS. In photonic MPLS, a label switched path in the wide sense, including not only the bit-stream but also an optical burst (packets) is achieved by photonic technologies.

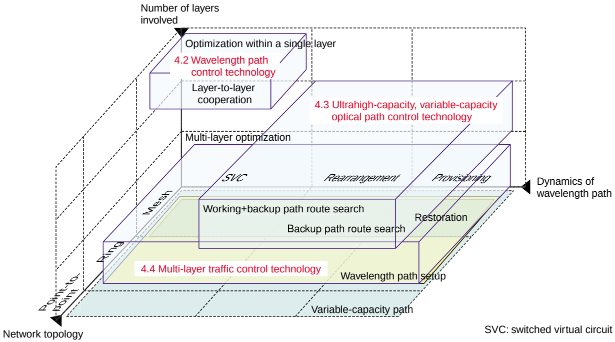

Fig. 1. Traffic engineering technology map.

aims to execute optimization in multiple layers in section 4.4. For details of other technologies for multi-layer path re-allocation and simultaneous path searching among working and backup paths, please refer to references [5] and [6].

3. HIKARI router system

The current IP backbone network is composed of IP and MPLS routers. Practical performances of the technologies for routing and forwarding IP packets are restricted by limits on electrical processing. Therefore, it will be difficult for a single IP or MPLS router to handle traffic demands, which are increasing faster than Moore's law because of the problems of increasing power consumption or equipment installation space. To break through the barrier of electronic technology, it is essential to introduce photonic technology. NTT Network Innovation Laboratories has proposed the concept of photonic MPLS that utilizes optical signals as a label and has advanced the development of the HIKARI router (i.e., photonic MPLS router), which is an IP router system seamlessly integrating IP, MPLS, and photonic MPLS by introducing photonic MPLS into the IP/MPLS router system [4].

The structure of the HIKARI router is shown in Fig. 2. From the hardware viewpoint, it is composed of four units: 1) Layer-2 and Layer-3 switching units (L2/L3 trunk units) such as IP routers, MPLS switches, and Ethernet switches, 2) wavelength routing units composed of optical switches, 3) the L1 trunk unit that executes Layer-1 signal processing such as monitoring the quality of optical path signals, optical signal regeneration, and wavelength conversion, and 4) a WDM transmission unit. From the software viewpoint, it is composed of blocks for IP control, MPLS control, photonic MPLS control, photonic network management, and HIKARI router management. The photonic MPLS control block and the HIKARI router management block are closely concerned with photonic network traffic engineering.

4. Photonic network control technology

4.1 GMPLS signaling protocols

In GMPLS, four LSP setting functions have been defined: PSC, TDM, LSC, and FSC*3-6. For LSP traf-

*3 PSC (packet switch capable): This indicates that it can perform label switching based on the value in the header's label field by adding another header to the packet.

*4 TDM (time division multiplexing): This indicates that it is TDM switch capable. It can perform switching using the time slot position in the multiplexing frame as a label, just like the SDH cross-connect system.

*5 LSC (lambda switch capable): This indicates that it can perform switching using the wavelength as a label.

*6 FSC (fiber switch capable): This indicates that it can switch optical fiber connections using a space switch by specifying the spatial position of the optical fiber as a label.

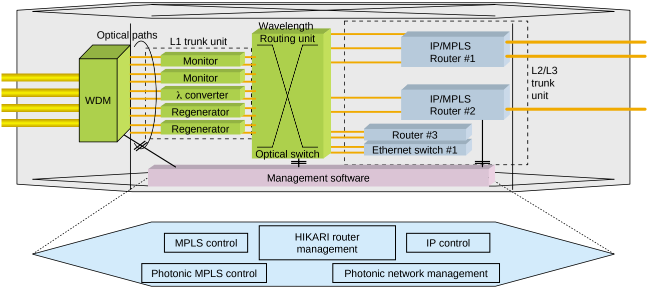

Fig. 2. Structure of HIKARI router.

fic control in MPLS, signaling protocols such as CR-LDP*7 and RSVP-TE*8 are used to set up the LSP by specifying the path route and bandwidth. These protocols are being expanded for GMPLS. Also in the HIKARI router system that was used for the live demonstration at SUPERCOMM2001, we implemented NTT's proprietary extended CR-LDP. To date, we have used a standard GMPLS-extended version of RSVP-TE for the HIKARI router system. NTT is developing various extentions targeting traffic control for the photonic network.

4.2 Wavelength path control technology

(1) Rooting and wavelength assignment (RWA) problem

A wavelength path can be defined as an LSP whose route is set up by an LSC system in GMPLS. In photonic MPLS, various optical labels besides wavelength have been defined. An LSP whose route is set up by optical label switching is called an optical LSP (OLSP). In this paper, we call an LSP that is set up by packet switching an electrical LSP (ELSP) and for contrast refer to an LSP that is set up by wavelength label switching as an OLSP.

To reduce the cost of the photonic network, it is essential to lower the cost of node systems. The transmission cost of link systems has been greatly reduced by the introduction of WDM technology, so the cost of O/E (optical-to-electrical) and E/O conversion within the node now accounts for most of the system cost. Since replacing ELSP switching by OLSP switching has already reduced the switching cost, it is currently necessary to reduce the OLSP cost by setting up the route without O/E or E/O signal conversion as much as possible. Wavelength path setup that does not (does) require O/E or E/O conversion is called "transparent" ("opaque"). With current technology, it is difficult to construct a large-scale network with a transparent method because of various physical restrictions. However, it will be possible to increase the transparency by allocating adaptively selectable Layer-1 transmission function to each node. Transmission functions include optical amplification, wavelength conversion, and optical signal regeneration through O/E and E/O conversion. This problem of adaptively assigning the wavelength path route and wavelength under various conditions is called the routing and wavelength assignment (RWA) problem. A comparison of using and not using wavelength conversion for the same traffic conditions and network topology showed that the required number of extra wavelengths was at most 5% [7]. This indicates that when a wavelength path route is determined for a given traffic flow pattern, under ideal conditions where it is possible to take enough time to decide the

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*7 CR-LDP (constraint-based routing label distribution protocol): This is one of the protocols for setting up a label switched path (LSP). A function that can specify the route explicitly by expanding the label distribution protocol (LDP) that distributes the label values of LSPs according to the shortest path routing used in IP routing has been added.

*8 RSVP-TE (reservation protocol traffic engineering extension): This is one of the protocols for setting up LSPs. It is an expanded version of RSVP for use in MPLS.

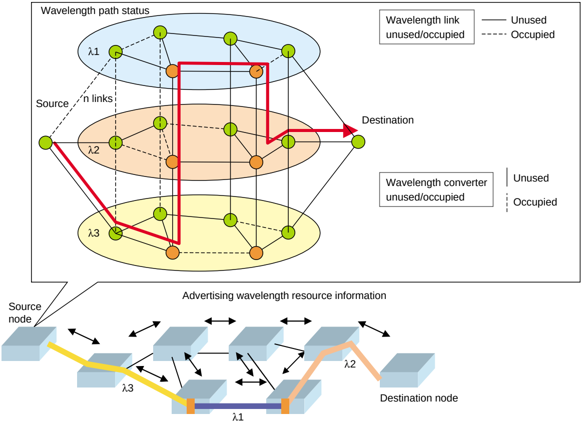

Fig. 3. Approach based on routing protocol.

path route and assign the wavelength, it is possible to set up the wavelength path efficiently without using wavelength conversion. However, since it is generally impossible to forecast future traffic demands, it is necessary to select the route and wavelength that are thought to be optimum by solving an RWA problem autonomously and distributively every time a wavelength path setup request is generated. In the case of central control by NMS, it is assumed that enough time is available to solve the RWA problem. On the other hand, in the case of distributed control, we need an algorithm that operates as fast as possible and generates as little invalid resource usage as possible. We have developed two approaches to setting up the wavelength path distributively considering the RWA problem: one utilizes a routing protocol and the other utilizes a signaling protocol.

① Approach using a routing protocol

The usage status of each fiber link (usage rate and list of unused wavelengths) is advertised by the routing protocol, and the wavelength to be used is determined when the route of the wavelength path is determined. In a transparent network, the shortest route along which the same wavelength can be assigned is sought. This method is based on selecting the shortest path to the desired destination in the topology in which an active link is eliminated at each wavelength plane*9. As a measure of the shortest route, both the physical distance and the optical fiber link usage rate are considered. Both are expressed in terms of an appropriate unit (for example, cost). The route giving the smallest value (e.g. cost) is selected. When a wavelength converter or an optical signal regenerator is inserted, advertising is performed to reflect the new cost of these devices corresponding to their usage ratio. When solving the RWA problem, reusing the same wavelengths as much as possible reduces the number of wavelength converters. That is, it is important to develop an algorithm that can obtain the shortest route by making the path as transparent as possible. Figure 3

*9 Wavelength plane: A logical concept representing the network topology. Each wavelength of those multiplexed onto an optical fiber (link) is regarded as a wavelength plane. For example, a wavelength plane is formed from the links in which wavelength λ1 is multiplexed. Wavelength planes are connected to each other by a wavelength converter.

shows the concept of resolving the RWA problem by routing. In the case of advertising by routing protocol, the time until the updated information is received by all nodes is relatively long. Therefore, during OLSP setup, resource reservation might fail because the RWA problem was solved using old information.

② Approach using a signaling protocol

A route is decided first by using a routing protocol and then a wavelength is assigned by using a signaling protocol. This approach is explained below for GMPLS-extended RSVP-TE protocol as an example. In RSVP-TE, a "Path" message is transmitted from the ingress node of the OLSP to neighboring nodes in turn and a label is hunted for hop-by-hop. At this time, a list of wavelengths that the upstream node can use is reported to the downstream nodes. In a downstream node, wavelengths that the node cannot use are deleted from the wavelength list and the list is passed on to downstream nodes. That is, the result of the Boolean AND operation on the list of wavelengths reported from the upstream node and the list of wavelengths that cannot be used in the node itself is transferred to the downstream nodes. When the Path message arrives at the egress node of the OLSP, the list contains only wavelengths that can be used by all the nodes on the OLSP route. One wavelength is selected from this list and is reported in reverse to the starting node by a "Resv" message. In this way, it is possible to assign the same wavelength to the whole OLSP. For transferring the wavelength list, a "LabelSet" object is utilized. This algorithm is called the "AND" type.

In the above algorithm, if no available wavelengths remain at a transit node, a route setting error is returned. However, if wavelength conversion is possible, it is performed once in that node, and the available wavelength list is initialized, then "Path" message processing is resumed. If it is impossible to reserve the wavelength converter in the transit node, a supplementary algorithm can be used such as searching (back tracking) for a node where it is possible to execute wavelength conversion or the algorithm can give up and try another route.

Figure 4 (a) shows the signaling methods of the

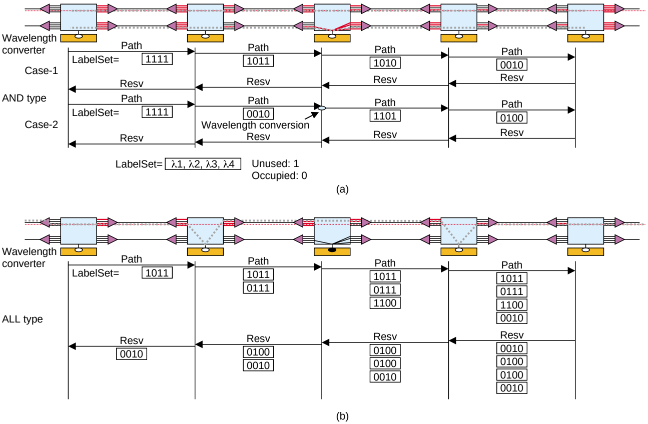

Fig. 4. Approaches based on signaling: (a) AND and (b) ALL types [10].

AND type. Consider four wavelengths: λ1, λ2, λ3, and λ4. Wavelength availability is indicated by a four-bit "LabelSet". If all four wavelengths are available, "LabelSet" is set to "1111". If any wavelength is unavailable, a corresponding "0" is assigned and stored in "LabelSet". In case-1 shown in Fig. 4(a), λ3 is finally available. In case-2, although there are no available wavelengths at one transit node, it is possible to find one by using a wavelength converter: the path segment up to that node is set using λ3 and that after is set using λ2.

Another algorithm decides the wavelength and the location of wavelength conversion by communicating round-trip path information and the "Resv" message. The "Path" message carries the information about wavelengths available at each hop and the status of wavelength converters in "LabelSet" and transfers it in stacked form. According to the information transferred in such a way, the link wavelength and the wavelength conversion location are decided at the egress node of the OLSP, and are assigned by the "Resv" message. This algorithm is called as "ALL" type because it transfers all the information in stacked form.

Figure 4 (b) shows an ALL type signaling example. "LabelSet" which contains unused wavelength information at each node is stacked and transferred to the downstream node. At the egress node, the assignment of [λ3, λ2, λ2, λ3] is decided based on the transferred information, and the assigned wavelength is reported back by piggybacking on a "Resv" message.

(2) Selecting the routing approach or the signaling approach

The routing approach requires solving a complex RWA problem, but may enhance the utilization of wavelength resources. In contrast, the signaling approach enables high-speed OLSP setting by solving a simple RWA problem, but does not optimize the wavelength resources on the scale of the whole network.

Which approach and which algorithm to select is decided depending on the time required to set up the wavelength path (signaling time or time required to advertise the routing information, etc.) and the average time taken to generate the request for setting up the new wavelength path and releasing. If the algorithm is utilized to re-configure a slow-traffic-driven network in which wavelength path set up or release requests are generated on the order of months, days, or hours, the time required to set up the wavelength path is very short compared with the time interval required to set up the next wavelength path. In such a traffic condition, both the routing and signaling approaches can be applied. When it is considered better to try to use wavelength resources effectively than to shorten the wavelength path setup time, the routing approach is more effective. On the other hand, in the case of burst transmission such as situations where wavelength paths are repeatedly and frequently set up and released at each content transmission under customer control, wavelength path setup must be done as quickly as possible, so the signaling approach is more effective.

4.3 Ultrahigh-capacity, variable-capacity optical path control technology

(1) Variable-capacity optical path

The transmission speed of the interface card installed in IP routers has risen steadily year by year: from 155 Mbit/s, through 622 Mbit/s, 2.5 Gbit/s, and 10 Gbit/s, to 40 Gbit/s, and has caught up with the inherent speed of the interface installed in the transmission systems. Since transmission systems must support transmission distances ranging from a few tens to several hundreds of kilometers, while IP routers must support transmission distances of only a few meters to a few kilometers, it is expected that we will soon enter the era where the transmission speed of IP routers is higher than that of the transmission system. In such a case, the transmission system must have a function that provides a single virtual wavelength path by bundling multiple wavelengths, which is called a virtually concatenated optical path (VCOP) [8]. VCOP can provide an ultrahigh-capacity optical path, but the capacity cannot be changed after it has been set.

Because wavelength is a valuable resource, it should be used as efficiently as possible by dynamically changing the number of bundled wavelengths depending on the traffic volume. By applying a traffic engineering technique to VCOP, it is possible to introduce a new, variable-capacity VCOP system that provides a variable-capacity optical path by dynamically changing the number of wavelengths (number of members) to be bundled. When making a variable-capacity optical path by controlling the number of members, it might not be possible to increase the volume because of wavelength reservation failure. Therefore, the variable-capacity VCOP is applied to services whose Service Level Agreement (SLA) does not guarantee to reserve bandwidth, such as a best-effort service.

(2) Variable-capacity VCOP control technology

A VCOP is constructed from multiple wavelengths. In this paper, each wavelength path in a VCOP is called a VCOP member. In the previous fixed-capacity VCOP, it was possible to provide the VCOP by using a relatively simple method that assigned an upper-layer's signal connected to VCOP to an individual member in turn at the ingress/egress points of VCOP. In contrast, in a variable-capacity VCOP, several new functions are required such as:

- measuring the traffic volume of upper-layer signals,
- judging the number of VCOP members that should be increased or decreased according to the corrected data, and
- changing the assignment of upper-layer signals to VCOP members.

The upper-layer traffic volume can be easily measured when the upper-layer device (L2/L3 trunk unit) and the VCOP termination point (wavelength routing unit) are merged, as in the HIKARI router. For signal assignment to VCOP members, a link capacity adjustment scheme (LCAS) [9] has already been standardized. It is achieved by expanding the LCAS for a one-wavelength link to a high-capacity link consisting of multiple wavelengths.

(3) Evaluation of variable-capacity VCOP control method [10]

In order to increase or decrease the number of VCOP members corresponding to the traffic volume in the upper layer, it is necessary to forecast the change in the upper-layer traffic volume. If the change in volume is large, then VCOP members may be set and released frequently and too many instant line drops may occur when volume changes are generated. To decrease the effect of instant line drops, we tried to control the number of VCOP members in resolutions ranging from several minutes to one hour. Figure 5 shows the controlling procedure.

① Traffic measurement

First, measure the traffic volume with time interval Tc and store the obtained results as traffic data.

② Judgment

Judge whether the number of VCOP members should be increased or decreased with time interval Ti by taking the forecast of change in traffic volume into consideration so that the quality of upper-layer traffic may be kept well, e.g., minimize the traffic loss or congestion time. For forecasting the change, utilize the traffic data stored in step (1).

③ Change of settings

If the number of VCOP members is increased, this procedure determines the route and the wavelength of the VCOP members to be created and executes signaling to set them up. If it is decreased, it determines the VCOP members to be released and executes signaling to release them.

For evaluation, we used a simple forecasting method based on the past tendency to increase/decrease traffic as a method of forecasting the traffic volume. We observed the traffic with a time

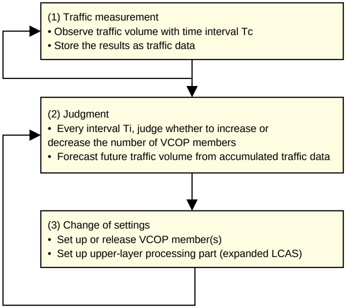

Fig. 5. Variable-capacity VCOP control procedure (VCOP: virtually concatenated optical path).

interval Tc, and calculated the expected value of traffic volume from current time to Ti using a linear approximation based on the past traffic data (we went back five intervals (5Tc) in our evaluation) at a time interval of Ti. When changing the VCOP settings, we assumed that it was possible to set up all the VCOP members with the same route for simplicity. The evaluation results are shown in Fig. 6. In this evaluation, we assumed that Tc was 30 min, Ti was 60 min, and 10 variable-capacity VCOPs could be set up between nodes. To each VCOP, we applied a traffic volume change ranging from 0.8 Gbit/s (min.) to 8.8 Gbit/s (max.) with a time interval of 24 hours (the phase change was random). Since the bandwidth of each VCOP member was 2 Gbit/s, each VCOP could handle up to five members. From Fig. 6, we can see that the maximum number of required wavelengths has been reduced to 39, and 22% resource reduction was achieved. Congestion occurred for only 2% of the time (0.6 times per day per VCOP) in this case.

Issues remaining for the future for practical application of the variable-capacity VCOP technology include establishing a traffic volume forecasting methodology to satisfy the required communication quality, developing a design methodology of maximum allowable route difference in expanded LCAS, and developing a VCOP member route decision algorithm that satisfies this maximum allowable route difference.

4.4 Multi-layer traffic control technology

(1) Multi-layer routing

The HIKARI router has both packet and wavelength switching capabilities (PSC and LSC). It is possible to dynamically, autonomously, and distributively set up and release both ELSPs and OLSPs by using GMPLS. When a request to set up an ELSP is generated in response to an increase in traffic volume in the IP layer, it sets up an OLSP, if needed, taking into consideration the resource usage conditions in the ELSP and OLSP layers. By route optimization considering the multiple layers, it is possible to reduce the required network resources by up to 50% [5]. In multi-layer traffic engineering that optimizes multiple layers at the same time, the amount of calculation increases in proportion to the square of the number of

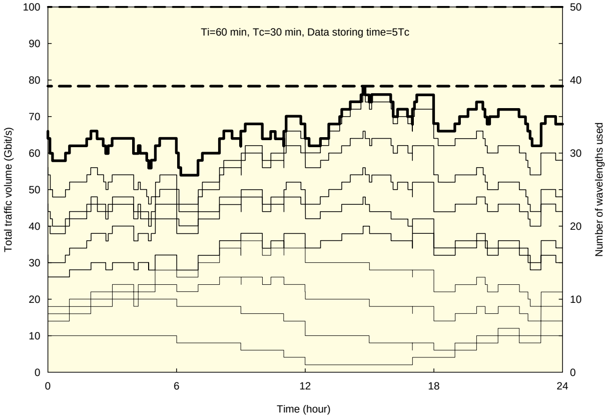

Fig. 6. Effect of resource reduction by variable-capacity VCOP.

layers, so this has not been taken up as a practical control method. However, with recent improvements in CPU performance, it is now being reevaluated as a method of handling multi-layer traffic.

Figure 7 shows a flow diagram of multi-layer routing. When an ELSP setup request is generated, the ELSP routing process is executed first. During this process, if it is judged that OLSP setting should be executed, then the OLSP routing process is started mid-way through the ELSP routing process and OLSP setup is executed. The result of the OLSP routing process is returned to the ELSP routing process and the ELSP process continues. Finally, judgment of whether or not the ELSP setup request is permitted is done. There are two approaches to setting up an ELSP in each layer: by routing or by signaling, as described in section 4.2 (1). In the current state of the art, since the time required for calculation is relatively long, the routing approach is expected to be used in traffic conditions where it is applicable.

In the HIKARI router, we are proceeding to implement the multi-layer routing process considering two policies related to OLSP settings. For a new ELSP setup request, if there is an existing directly connected OLSP that can accommodate an ELSP, both policies utilize it. If there are no directly connected OLSPs, then the two policies use different algorithms. In policy #1, an existing OLSP is used as much as possible. In this case, the ELSP is accommodated in multiple OLSPs with multiple hops. In policy #2, a

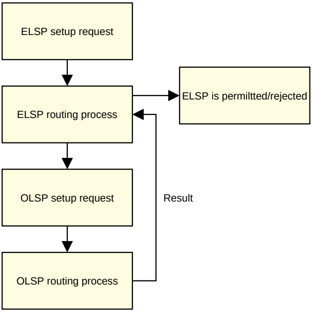

Fig. 7. Flow diagram of multi-layer routing.

new directly connected OLSP is set up. If this cannot be done, multi-hop accommodation is tried.

Details of the multi-layer routing setup procedure are given below:

Policy #1

a) Check whether there is a directly connected OLSP that can directly accommodate the bandwidth of the newly setup ELSP. If there is one, jump to step d); if not, go to step b).

b) Search for an OLSP that can accommodate the bandwidth in multiple hops within the maximum number of hops that was given beforehand. If there are multiple OLSPs, select the one that gives the minimum number of hops. If there is one, jump to step d); if not, go to step c).

c) Check whether a directly connected OLSP can be newly set up. If it is possible, go to step d); if not, jump to step e).

d) Permit the request for setting up a new ELSP.

e) Reject the request for setting up a new ELSP.

Policy #2

a) Check whether there is a directly connected OLSP that can directly accommodate the bandwidth of the newly setup ELSP. If there is one, jump to step d); if not, go to step b).

b) Check whether a directly connected OLSP can be newly set up. If it is possible, jump to step d); if not, go to step c).

c) Search for an OLSP that can accommodate the bandwidth in multiple hops within the maximum number of hops that was given beforehand. If there are multiple OLSPs, select the one that gives the minimum number of hops. If there is one, go to step d); if not, jump to step e).

d) Permit the request for setting up a new ELSP.

e) Reject the request for setting up a new ELSP.

(2) Performance evaluation

We evaluated the blocking ratio of ELSPs for the two multi-layer routing algorithms of policies #1 and #2 using the National Science Foundation (NSF) network model shown in Fig. 8. In this evaluation, we assumed that there was a bi-directional pair of optical fibers in the link between nodes, the number of wavelengths per fiber was 8, and the transmission speed of each wavelength was 10 Gbit/s. We also assumed that the generation of ELSP setup requests had a Poisson arrival distribution[*10] and the withholding time had

*10 Poisson arrival distribution:It is often used as a model for the number of events (such as the number of telephone calls at a business or the number of accidents at an intersection) in a specific time period. The Poisson distribution is determined by one parameter. Each event occurs independently.

an exponential distribution. For simplicity, we assumed that the required bandwidth of ELSPs was fixed to 500 Mbit/s and the source-destination pair traffic volume had a uniform distribution. When no ELSPs were accommodated in the OLSP, the OLSP was released to free up the wavelength resource. The relationship between the traffic volume that can be accommodated in the source-destination pair at which the blocking ratio of ELSP setup request (request refusal ratio) is less than 0.01 and ρ the maximum number of PSC ports available at the same time within node is shown in Fig. 9. The value of ρ indicates the number of OLSPs that can be terminated at the node. The results in Fig. 9 indicate that policy #1 showed better performance than policy #2 for ρ<10. In contrast, for ρ>10, policy #2 was better than policy #1. When ρ is small, blocking occurs mainly as a result of absence of unused PSC ports. Therefore, policy #1, in which existing OLSPs are used as much as possible and ELSPs are bundled with as few OLSPs as possible, can accommodate more traffic than policy #2. On the other hand, when ρ is large, blocking is caused mostly by the shortage of wavelengths. Therefore, policy #2 in which directly connected OLSPs are set up first and multi-hop connection is executed by using PSC ports when the wavelengths becomes scarce, can utilize the resource more effectively than policy #1.

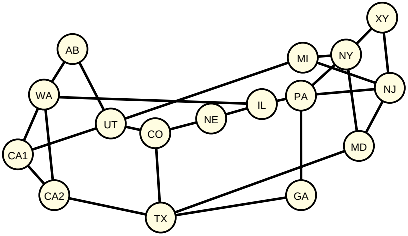

Fig. 8. NSF network model.

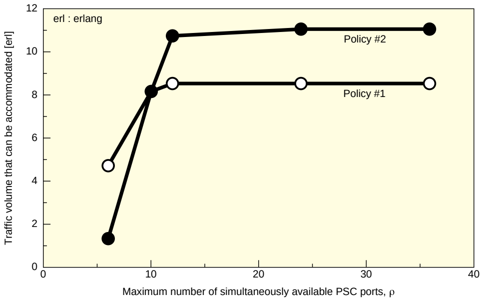

Fig. 9. Traffic volume that can be accommodated.

From the above results, we found that, when the number of wavelengths was fixed, there was an appropriate region for applying the policies depending on the maximum number of PSC ports that were simultaneously available. Therefore, it is desirable to make both policies available in the HIKARI router and to choose one or the other according to the situation. In other words, it is desirable to change the node settings in the following way: if there are many small nodes (ρ is small) when the network operation starts, policy #1 should be selected. Then, as the number of large-scale nodes increases (ρ becomes large), policy #2 should be selected. In future, it will be necessary to evaluate the behavior of the system when both policies exist together in the same network.

5. Conclusion

In this paper, we proposed traffic engineering technology based on distributed control as a base technology for creating novel photonic network services. It will allow wavelengths to be used efficiently, provide high-volume transmission lines (wavelength paths) promptly, and support both regular and irregular changes in traffic volume adaptively. This is effected by using the wavelength path control technology based on GMPLS high-speed signaling, ultrahigh-volume variable-capacity wavelength path control technology, and multi-layer traffic control technology.

The traffic control technology presented in this paper can be applied to the HIKARI router, which is expected to enable effective operation of photonic IP networks as well as achieve multi-layer control. Although our current HIKARI router handles multiple switching capabilities (packet switching (PSC) and wavelength switching (LSC)), it is scheduled to be expanded in the near future to handle various sets of layers including i) packet switching and time division multiplexing and ii) packet, wavelength, and fiber switching.

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