A study on photonic Network Architecture

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We study photonic network architecture based on phtonic packet switching. This is a promising architecture for use in one or two decades, when the amount of traffic will increase tremendously. In order to apply our architecture to a backbone area of a network, it is inevitable to construct a photonic network that has a large link capacity, high-throughput node capability, and intelligency. We mention problems that should be solved for the application. These are related to our future plan, which is to investigate on efficient contention resolution, efficient routing, reliability and migration as well as network architecture itself.

1 Introduction

With the rapidly growing popularity of the Internet has come a rapid increase in network traffic volume. Demand is expected to grow for large-capacity networks of the packet-switching type capable of efficiently transporting data traffic, which already exceeds telephone voice traffic in volume. The switch nodes in the network backbones may also need to have traffic switching capability (throughput) of Tbps to Pbps order. The switching capabilities of present-day technologies such as IP (Internet protocol) and ATM (asynchronous transfer mode) are soon expected to reach their limits, due to constraints upon memory access speed and processing speeds of LSIs in processing packet headers. It is believed that optical technologies will be required to realize large-capacity networks.

Use of optical technologies in switch nodes would permit the switching of broadband signals across optical fiber connections without optical-electrical (O/E) conversion. That is, photonic networks could be built in which data sent from an edge node is forwarded to a receiving edge node without being converted to electrical signals. The introduction of such photonic networks would provide significant advantages, including simplified switch node apparatuses, higher bit rate transmission lines, and reductions in overall network system costs.

The fields in which photonic networks may find applications are numerous and varied. Rather than access systems for ordinary residences such as FTTH (fiber to the home) and an office/campus LANs [1], the area that we are currently targeting is the network backbone to which traffic from such end users concentrate. By focusing on backbone systems, we hope to provide high capacity and high throughput for transmission links and switch nodes using optical technologies, and to improve network throughput (defined in this paper as the sum total of the traffic volume received at the edge nodes of a network backbone).

Surveying trends in optical technology pertaining to the construction of backbone networks, we see that equipment in which traffic per fiber equal to 100 Gbps or more is transmitted using WDM (Wavelength Division Multiplexing) technology has been brought to the commercial stage for transmission links. At the experiment level, the gains in traffic throughput achieved through such technologies have already reached levels on the order of a few Tbps. These studies achieved such high traffic volumes by multiplexing several wavelengths, each carrying optical signals of 2.5 to 10 Gbps, across a single optical fiber, using lightwave in the 1.55 μm band. Providing optical fiber bundles in which WDM optical signals flow between the switch nodes enables the construction of networks with large-capacity links (e.g., [2]). Moreover, WDM technology is capable of functioning with the current base of installed single-mode fiber networks for low-cost implementation of large-capacity links.

Optical technology has already been applied to switch nodes, with commercial applications such as optical add-drop multiplexers (OADM) and optical cross-connects (OXC). Large-scale OXCs are currently under development incorporate optical micro-electro-mechanical systems (MEMS). Current research on network configurations [3][4] will also enable large-capacity photonic networks, given proper integration of these technologies.

However, while OXCs offer broadband characteristics, they provide poor switch node functions, raising the prospects of having a smaller proportion of the data assigned to each wavelength in the bandwidth of the WDM link (traffic accommodation efficiency). While OXC enables transmission of optical signals between non-neighboring nodes, problems remain in terms of high throughput and efficiency. Packet switching at switch nodes is efficient in order to increase traffic accommodation. For high-speed packet switching, optical rather than electrical packet-switching is desirable.

We are thus investigating photonic packet-switched networks [5][6][7][8], one of photonic network systems capable of realizing a large-capacity, high-throughput network. We examine three specific areas: a large-capacity optical network architecture; contention control to improve throughput at the switch node; and routing to make effective use of resources in the network and to improve network throughput. Additionally, in order to provide high reliability, the network must also have the capability to perform automatic restoration as in existing IP networks and SONET/SDH (synchronous optical network/synchronous digital hierarchy).

Meeting all these requirements given the current state of optical technologies is not easy. In this study, we explore a photonic packet-switched network that maximizes optical technologies and the advantages they offer while minimizing the use of electronic processing technology. Several configurations have been proposed for so-called photonic packet switches [9][10][11][12][13][14]etc.. The difference between such switches and the photonic packet switch considered in this study will be described in Chapter 2.

Optical technology can increase total network throughput and provide each user greater bandwidth for data communications. On the other hand, it is difficult to provide varying qualities of service (QoS) for each user. Implementing a range of QoS functions is most easily done using electronic processing technology, since the task involves complex queuing and routing. However, performing the necessary processing across a network makes it difficult to implement the advantages of optical technology and decreases throughput. To provide QoS without decreasing throughput, we must apply optical technologies and electronic technologies in different spheres. One solution is to implement QoS at the edge of a network, using electronic technologies. To maintain high throughput, it also helps to implement control of traffic entering the network at the edge. Thus, we also investigated more sophisticated edge node system functions that rely on electronic technology. The assignment of functions in the network described is illustrated in Fig. 1.

This paper is organized as follows:

Progress in photonic network architectures is briefly described in Chapter 2, followed in Chapter 3 by a discussion of the photonic network architecture proposed here. Future research directions are outlined in Chapter 4. Chapter 5 provides a summary of the paper.

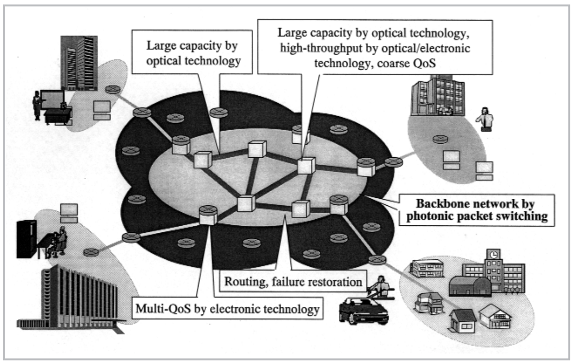


Fig.1 *The roles of the backbone network*

2 Progress of optical network architectures

2.1 WDM link network

In these networks, switch nodes are implemented based on electronic technology. The transmission links between the nodes are enhanced to achieve large capacity using WDM technology. IP over WDM [2][15] falls into this category. The switch node (router) of the IP over WDM compares a header of an IP packet with a routing table and determines an output port, a process called “forwarding.” When the traffic volume arriving at the router increases past certain levels, the router may be unable to process all the arriving packets due to bottlenecks in access speed to routing tables in memory. Compared to increases in link capacity provided by WDM technology, increases in processing capability by electric technology are small [16]; thus, the introduction of the WDM technology does not always yield a significant increase in network throughput. Moreover, increasing the numbers of switch nodes between transmitting/receiving terminals can lead to delays at the switch node.

2.2 WDM lightpath network

A recent topic of great interest in the field of packet-switching network architecture is a method whereby part of the traffic flowing through the WDM link is switched only by OXCs or OADMs. If all traffic is switched solely by OXCs, the network becomes a photonic network called a (WDM) lightpath network [3]. At the source node, data is converted into an optical signal of a certain wavelength and propagated across the network. Since the wavelength serves as an identifier in the OXC, the OXC switches the optical signal to a proper downstream link. The wavelength can be assigned to each of the destination nodes as an identifier thereof. However, this method is not appropriate for large-scale networks, since the number of discrete wavelengths that can be used for long-distance transmissions is considered to be limited to the range of 100 to 1000, limiting the number of receiving nodes in such a network.

Various proposals have been put forward involving packet-switching networks that incorporate WDM and the OXC to produce significant gains in capacity. From the point of view of the IP network, these proposals come under the heading of IP over WDM networks that use MPλS (multi-protocol lambda switching) [17]. On the other hand, from the perspective of optical technology, the networks are categorized as lightpath networks [3] and multihop lightpath networks [4]. The characteristics of WDM lightpath networks will be described here in terms of IP over WDM networks. However, these features are common to all such networks.

As described above, the OXC executes switching according to wavelength but performs no processing at the packet level. The OXC switches part of the traffic input to a certain router, whereby a router downstream of the router can switch additional traffic. This increases network throughput and reduces delays between the source and destination of signals switched by the OXC.

Nevertheless, there are certain problems associated with the traffic accommodation efficiency of the fiber. The OXC cannot multiplex different pieces of data, each having the same wavelength and input from a different route into the same output port as a piece of data having the same wavelength. Wavelength assignment to the IP packet is determined by the router by referring to the IP routing table, it may happen that traffic of a certain wavelength is scarce. The OXC cannot output the traffic from different routes into the same wavelength, thereby limiting efficient use of the bandwidth provided by the wavelength.

There are two typical methods for making the most efficient use of the bandwidth (transmission capacity) of a wavelength. One is to reduce the bandwidth of the wavelength, in effect increasing the number of wavelengths. The prospect of a WDM of 1000 discrete wavelengths is becoming increasingly realistic [18], and a method for constructing a network with the use of these wavelength is currently being examined [19]. However, handling signals of an order of Tbps to Pbps requires additional optical processing apparatuses at the switch node, and problems remain in terms of possible scale and cost. The other technique is to apply approaches [20][21][4][22] involving routing (processing to make a routing table that indicates an output route of the traffic having entered the switch node by using topological information of the network). As a result, for a number of nodes with low traffic output, the router outputs traffic by accommodating all such traffic in a single wavelength for effective use of the bandwidth of that wavelength. However, packet-switching capacity based on electronic processing has inherent limits, as described above. Ideally, packet-switching should be performed on an optical layer. This is described in the next section.

2.3 Photonic packet-switched network

A network that uses photonic packet switches is a photonic network that performs packet switching at the switch nodes. The data part of the packet is not converted into electrical signals at any point along the path. Unlike the OXC, since this photonic network can switch a packet that has the same wavelength and has been input from a certain port to multiple ports and can switch packets that have been input from multiple ports to the same port, it offers excellent traffic accommodation efficiency to the link. A photonic packet-switched network can be categorized into the following two categories, by differences in forwarding method.

2.3.1 Electronic addressing

In this technique, header of packets are converted into electrical signal and then forwarding (addressing) is operated electrically. Research and development into photonic packet switches using this method has been performed at numerous facilities, and switch prototypes having transmission links of 10 Gbps or so per wavelength are currently under development for use in a node system [9][10][11][12][13][14]. While these switches can accommodate traffic in the link efficiently, since electronic addressing becomes more difficult with increasing speed of the transmission link, increasing the speed of the transmission line and simplification of the equipment may not be realized as expected. Since the packet switch is more complicated than the OXC, there appear to be no dramatic advantages compared to the WDM lightpath network unless transmission speeds over lines can be improved.

Another proposed technique reduces the transmission speed of the header to facilitate electronic processing and increases the transmission speed of the data part to achieve a large-capacity network [13]. However, this technique results in a large header-to-packet time ratios, a factor that hinders adequate network throughput. (Packet switches for fixed-length packets are also known as optical ATM switches.)

2.3.2 Optical addressing

Optical addressing optically collates the packet header with the routing table, enabling high-speed forwarding. With the removal of the electronic bottleneck, forwarding is possible even when the bandwidth of one wavelength is raised as high as 40 Gbps or 160 Gbps, with higher throughput at the switch node. Table 1 shows the features of a network that uses OXCs and photonic packet switches. The table compares a method for performing optical addressing against another method.

Table 1 *Comparison of network features and problems*

Network (NW)	IP over WDM NW		Photonic packet switching NW	
Node architecture	OXC only	OWC+IP router	Electronic addressing	Photonic addressing
Data-to-link speed radio	Small	Large	Large	Large
Main bottleneck	Number of Wavelengths	IP router's processing	Addressing, Header overhead	Contention resolution (Chap.3)
Link speed	>10Gbps	10Gbps	10Gbps header	40Gbps
O/E conversion	Unnecessary	Router IN/OUT	Header	Unnecessary
Number of addresses	3,000	$2^{\text{bit length}}$	$2^{\text{bit length}}$	>10,000[6]

Table 2 *Application area of the optical technology to the packet switch*

	IP router	OXC	Photonic Packet Switch	
			Electronic addressing	Photonic addressing
Addressing	E	O (MEMS, etc.)	E	O (MS-FBG, etc.)
Switching	E		O (Gate SW, etc.)	O (Gate SW, etc.)
Buffer architecture	E	Unnecessary	E[10],O[11]	O
Contention Resolution	E		E	E
Routing	E	E	E	E
Examples	(Many)	(Many)	FRONTIER[11], WASPNET[12], TAOS[10], etc.	MλLSN[5], OCDM-SW[23]

O:optical E:electrical

For optical addressing, an optical code (OC) is assigned to the header, and the difference of the codes is analyzed optically [23][24]. However, WDM technology is considered more practical at this time. We have proposed a format in which the packet is composed of multiple number of wavelengths and the photonic packet switch that identifies addresses by analyzing combination of wavelengths [5][6]. The next chapter describes a network architecture that incorporates this concept.

3 Photonic packet-switched network

This section provides an overview of a network that uses the photonic packet switches (multi-wavelength label network) shown in 2.3.2.

3.1 Packet format using multi-wavelength label

Fig. 2 shows the format of the optical packet. A wavelength band (λ-band) of multiple wavelengths (λ_{1A}-λ_{1E}) constitutes the packet. The wavelength band is divided into two groups. One is set aside to serve as the header containing the address ($\lambda_{1A\text{-}1D}$; number of wavelengths: W), while another is set aside for the payload (λ_{1E}). The address (multi-wavelength label) consists of K chips, and is identified according by combination of the wavelengths and their permutation along the time axis. For example, the address information for an optical packet in which wavelengths are aligned as "BADC" differs from that of the packet in FIG. 2. If W and K are assumed to be W=16 and K=10, it becomes

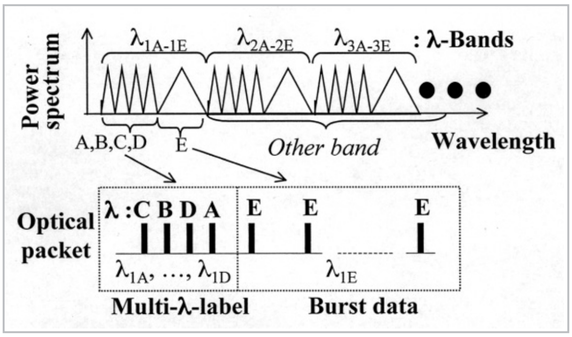


Fig.2 *Optical packet format that uses a multi-wavelength label*

possible to provide a range of over 2^{32} addresses [6]. The packet length is set to a fixed length for faster contention resolution.

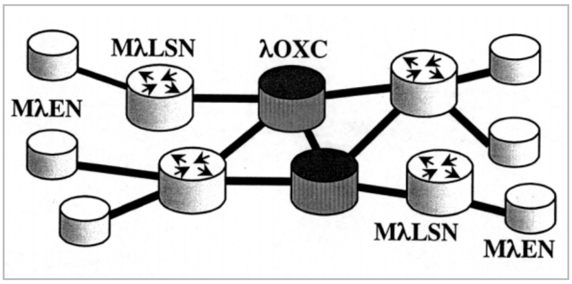


Fig.3 Multi-wavelength label network

3.2 Multi-wavelength label network

Fig. 3 shows a multi-wavelength label network. A multi-wavelength label switch node (MλLSN) that acts as a photonic packet-switch node analyses the multi-wavelength label and performs switching. Use of the MλLSN makes it possible to perform more detailed routing. However, introduction of the OXC to output all packets whose wavelength bands are the same in the same direction is also necessary to keep down costs.

The differences between the multi-wavelength label network and the lightpath network are explained below. In WDM lightpath networks, as described in Chapter 2, the wavelength is not used to identify the receiving node. On the other hand, since the multi-wavelength label network provides an adequate number of labels, the labels can be used to identify individual receiving nodes. For example, with only 16 wavelengths, the number of possible labels exceeds 2^{32}. This makes it possible to assign a unique label consisting of multiple wavelengths to each receiving node, even on networks as large as the Internet. These labels serve as addresses for optical packets and are used to perform forwarding at the MλLSN.

3.3 Photonic packet-switch node (MλLSN)

When the packet arrives at the MλLSN, the following processing is performed in order [7].

(1) Header-payload dividing: The packet is divided into the header and the payload, and generates the same number of copies as specified in the routing tables.
(2) Optical address collation: Correlation processing of the addresses in the header is conducted at a multi-section FBG (fiber Bragg grating) correlator. When the input address matches with a combination of the wavelengths of the FBG, the FBG generates a pulse having a high peak.
(3) Switching by the optical switch: A switch is driven by the pulse having the high peak of (2), and the payload is switched to an appropriate route.
(4) Header assignment: A header containing an appropriate address is assigned to the packet in accordance with the routing table.
(5) Contention resolution: Processing is performed to keep multiple packets from arriving simultaneously and colliding.

Experiments were performed for procedures (1) to (3) [5][6]. Fig. 4 shows an example of the experimental system (W=3, K=3). The packet containing the address "$\lambda_{1A}\lambda_{1C}\lambda_{1B}$" matches "FBG1*" of the three-section FGB, and the payload is output from Gate 1. The packet containing the address "$\lambda_{1C}\lambda_{1B}\lambda_{1A}$" is output from Gate 2.

Table 2 shows the areas of application of optical processing in the switching systems.

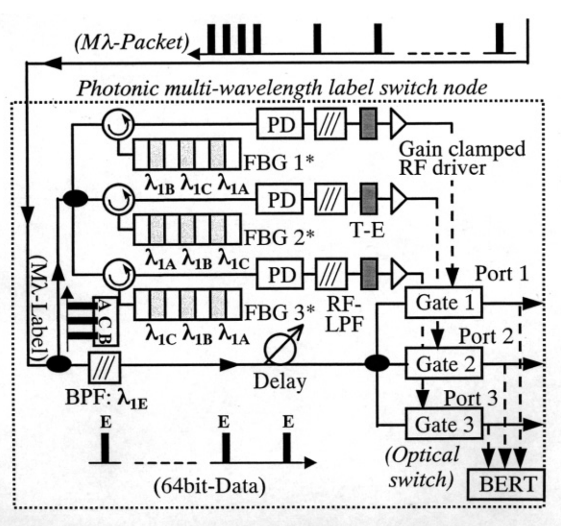


Fig.4 Configuration of a 1×3 optical switch at the switch node

MλLSN conducts addressing optically and resolves the maximum factor of the throughput decrease in the router and in the electronic addressing switch. As a result, the speed of the contention resolution processing accompanying logical and arithmetic operations becomes the maximum factor that governs throughput. Even if contention resolution processing is implemented electronically, it is not more crucial bottleneck. On the other hand, contention resolution processing is simplified by narrowing the network services provided. Since the time required for routing and the routing table rewrite time does not significantly affect throughput, routing and rewrites are performed electronically, not optically.

3.4 Advantages of the MλLSN and problems

3.4.1 Advantages

(1) Technologies for WDM devices in current use or currently entering commercial production, such as AWG (arrayed waveguide grating) and FBG, may be used for part of the MλLSN.

(2) Since different wavelengths are used for the header and for the payload, no overhead is incurred in terms of the throughput of the switch. Throughput is governed only by switching time.

(3) An optical signal of 40 Gbps or so can be switched by optical addressing. Moreover, the time required to perform addressing is governed by the speed at which light propagates.

(4) Routing tables storing over 10^4 address entries for each node can be compiled [23].

(5) If the buffer is placed on the output side of the MλLSN, the time from input to switching is fixed. This makes it easy to implement a synchronization function required for switching.

3.4.2 Problems

Listed below are topics for future research.

(1) Highly effective use of the bandwidth
(2) Synchronization
(3) Optical buffer
(4) Contention resolution

The reasons for these items are stated below.

(1) In the case of the multi-wavelength label, as bandwidth for the label wavelengths is expanded, usage efficiency of total bandwidth (ratio of the payload to the whole) decreases.

(2) Problems involving synchronization lead to more complex contention resolution.

(3) Since no optical RAM is currently available, we must consider buffer architecture that rely on multiple optical delay lines.

(4) To avoid collisions, a contention resolution processor must determine a residence time in the buffer until the packet undergoes addressing and arrives at the output buffer.

Resolving these problems will realize a switch node system with high throughput. To improve network throughput and increase reliability, other problems need to be solved cooperatively within the network, including routing and restoration issues. These problems will be described in Chapter 4.

3.5 Services provided by multi-wavelength label networks

This packet-switching network provides a best-effort-packet forwarding service. However, we need to consider that at source/destination edge nodes at which application software performs real-time communications, a bandwidth-guarantee-type service [7] is desirable. Moreover, some users require high-quality services rather than real-time services. For the Internet, the most popular packet-switching type network, Diff-Serv (differentiated services) and RSVP (resource reservation protocol) are currently being studied to guarantee communications quality between two points. ATM has a CBR (constant bit rate) class, which is already in service. Given these trends, photonic packet-switched networks would ideally use both the bandwidth-guarantee-type service and the best-effort-type service.

On the other hand, quality must be balanced against high-throughput. For example, providing advanced functions using optical nodes, such as establishing a number of priority classes or guaranteeing an average bandwidth for each flow, increases processing time. This most likely creates packet-switching bottlenecks and decreases the speed. For photonic packet switching networks, it is sufficient to provide services that guarantee maximum bandwidth, such as the CBR class of ATM. More complex quality hierarchies are implemented through functions of the edge nodes of the network.

4 Future research programs

As described in Chapter 1, we have been carrying out research on photonic networks in order to realize networks that feature large capacity, high throughput, and advanced functions. The multi-wavelength label network described in Chapter 2 is a candidate network architecture for a photonic network and this will expand the networks in the future. In this chapter, several approaches with the potential to expand into promising research areas are briefly presented.

4.1 Research on network architecture

Although optical technology transmits and switches large-capacity optical signals, optical signals are not always mapped with the data. For example, in the WDM lightpath network described in section 2.2, a dedicated path (a group of wavelength channels) down to the destination node (or an intermediate IP router) is established before data transmission. Thus, even when no data flows in a wavelength channel comprising the dedicated path, the wavelength channel cannot be used to forward other data.

This study examines network architectures that prevent waste of transmission capacity and maintain high traffic accommodation efficiency. To increase the traffic accommodation efficiency, traffic needs to be forwarded to empty bandwidths according to a routing table. This also renders the network resistant to small variations in traffic volume. The candidate architecture is a multi-wavelength label network, which is a photonic packet-switching network. In this network, since the traffic in the same wavelength band that arrive at multiple input ports at a switch node can be multiplexed the same output port, the traffic accommodation efficiency can be improved relative to that of WDM lightpath networks.

However, if all traffic is forwarded on a best-effort basis, packet loss will degrade quality and lead to network service problems. To ensure the bandwidth guarantee service described in section 3.5, we need to prepare a mechanism that sets the lightpath [7] and controls the bandwidth in the network or at a node.

4.2 Research on packet contention resolution

No dedicated path is provided for packets of best-effort traffic in multi-wavelength label networks. In this case, multiple packets may be simultaneously forwarded to the same output port at the switch node. Providing a node with a packet contention resolution function improves node throughput. We will then undertake research concerning the contention resolution of photonic packet-switch nodes. This research is divided into two subtopics: buffer architecture, and a contention resolution algorithm.

4.2.1 Buffer architecture

No practical optical RAM (Random Access Memory) is currently available. The most commonly considered methods for preventing packet collisions with optical signals involve shifting one of time, wavelength, or space. Contention resolution based on time uses an optical buffer composed of fiber delay lines [25]. There exists a method for reducing the numbers of fiber delay lines using wavelength division multiplexing and wavelength conversion technologies [11][12][13], a method whereby spatial contention resolution (deflection) is achieved [26]. Another article [27] proposes that a combination of the above-mentioned methods can be used to reduce the number of optical delay lines comprising the optical buffer. Articles [25] discuss various methods for constructing optical buffers.

Methods other than optical buffers are not suitable for multi-wavelength label networks. That is, a wavelength conversion method targeting 10 Gbps or so for a single wavelength and simultaneous conversion of all the wavelengths in a high-speed link is not practical yet. Moreover, this method requires such high-speed performance that wavelength selection is determined at the time when a packet enters the conversion equipment. Thus, the method is not suitable for multi-wavelength label networks. On the other hand, the application of deflection increases the possibility that packets addressed to the same destination will have different delays. This method requires rearranging of packet permutations at an edge of the network, making it impractical. Consequently, in this study, we restricted the methods that we considered to create optical buffers to those involving optical delay lines.

4.2.2 Contention resolution processing

The buffering method described in 4.1.1 is classified into three methods, according to the position of the buffer arranged at the switch node: an input buffer method; an in-switch buffer method; and an output buffer method. Among these, the output buffer method allows for the simplest multi-wavelength label switch configuration. In addition, the output buffer method excels in packet loss characteristics, in comparison with the other two methods. Thus, our efforts focused on the output buffer method.

In a delay line buffer, particularly a single-stage buffer [25], when the packet enters the delay line, a unique output time is determined. Therefore, to avoid a decline in throughput caused by collision with other packets, we need to determine a delay time (delay line to be selected) before which the packet arrives at the buffer. Since any packet arriving at the buffer arrives there after a fixed interval, the packet delay time must be shorter than the packet time. For example, if the optical packet length is 500 bytes, approximately equal to the default length of the IP packet, and the transmission speed of a certain wavelength is assumed to be 160 Gbps, packet length is equivalent to 25 nsec. In the output buffer method, as the number of input lines increases, higher-speed processing or multi-stage processing is required. In this study, we will examine a method whereby the delay time is determined in a time infinitesimally shorter than the packet time, which is equivalent to the length of a packet.

Further, if contention resolution processing is improved to provide advanced functions, the determination of a delay time will take longer. As described in section 3.5, the service classes in the network are minimized and high throughput emphasized.

Currently, multi-wavelength label networks are intended for fixed-length packets, with high-speed contention resolution processing to be implemented. When the multi-wavelength network architecture is applied to a network that handles variable-length packets, such as the Internet, variable-length packets must be converted/divided into fixed-length packets. In addition, to avoid such work load, we must examine contention resolution processing methods and packet switching methods capable of handling variable-length packets.

4.3 Research on efficiency improvement

Even if optical fiber transmits large data volumes and optical node provides large capacity and high throughput, small data flow in the network makes the optical merit meaningless. For example, in certain cases, traffic may exceed processing capability of some nodes and the network cannot forward all traffic, although there is no traffic in most of the other nodes. In this case, traffic throughput can be significantly improved if traffic exceeding the processing capability of the node is rerouted.

As part of this study, we will carry out research concerning network efficiency improvements. For example, Internet, routing protocols such as BGP (Border Gateway Protocol) and OSPF (Open Shortest Path First) are deployed for efficient use of resources.

The WDM lightpath network provides for a similar routing scheme (e.g., [20]). We then need to develop a routing method whereby network resources are used with high efficiency in photonic packet-switched networks. Also important are estimates of traffic patterns and flow based on measurements with a traffic monitor (described in section 4.4) and examinations of the timing determinations for re-routing and its procedures.

4.4 Research on high reliability

Even with large-capacity, high-throughput networks, there is no guarantee that networks will operate without failures. Existing networks such as the Internet and SONET/SDH have functions that perform automatic rerouting in the event of failure. In WDM lightpath networks, a technique is currently being studied whereby errors at the wavelength level and at the bit level are monitored and identified [28], and network routes automatically restored based on this information. We need to ensure that our proposed new networks do not have worse reliability than existing networks. Ensuring highly reliable photonic packet-switched networks requires implementing functions equivalent to those in WDM lightpath and other networks.

In this study, we will also develop a traffic monitoring function that locates a failure component and quickly acquires information pertaining to the failure. Given the importance of fast network recovery in the event of failure, we will examine routing that provides protection (a back-up route is secured in advance) and restoration (the route is altered in the case of failure).

By monitoring optical signals at the packet level in addition to the bit and wavelength levels, we can obtain the status of network resources clearly. This can then be used for routing to improve network traffic accommodation efficiency.

4.5 Research on migration from the WDM lightpath network

Of course, users are required in order to create traffic flow across a network. The WDM lightpath network provides OC48 and OC192 interfaces of connection to SONET/SDH. And also, a system that allows Internet traffic to flow by IP over WDM and the MPλS is currently being constructed. However, since the transmission speed of the targeted photonic packet-switched network will have high speeds exceeding 10 Gbps, it is unlikely that an interface for an apparatus with the use of the electrical technology will be provided. For the time being, there is no method for connecting the photonic packet-switched network to a router interface of 10 Gbps. Therefore, in this study, we will examine a system that provides an interface for electronic apparatus while traffic flows over the photonic packet-switched network.

Over the course of the next five years, WDM lightpath networks appear likely to become the mainstream for data traffic forwarding. To facilitate the migration of WDM networks to photonic packet-switched networks, we need to examine not only the interface for electronic apparatuses, but to consider a method for implementing a WDM lightpath architecture in packet-switching networks.

4.6 Research on advanced functions

As a network has a large capacity and increases throughput, end users hope multiple services using the large capacity. This will make it difficult to provide multiple QoS (quality of service) required by individual users in the end-to-end basis by using only simple buffer mechanisms at switch nodes. The provision of QoS may also come to include various features such as delay characteristics, reliability, security levels, and account tracking mechanisms, in addition to guarantees concerning communications bandwidth. Meeting these requirements requires processing for each user, for each stream, or for each packet, in accordance with the network status, or to conduct a control using coordinated functions between distributed nodes. These advanced functions can only be handled electronically. Since such processing decreases throughput, a configuration in which processing is implemented not in the optical backbone but at the edges or gateways appears most suitable.

In this study, we will perform research on a network control technology, including the advanced functions of the edge node system. For provision of end-to-end QoS, there are numerous studies that primarily focus on how QoS is realized in the form of the multicast services. In our study as well, we plan to examine the issue of end-to-end QoS from numerous perspectives. One promising technique is an active network technology involving powerfully enhanced node functions. We have advocated a stream code scheme [29][30] and introduced a method for realizing basic network functions. Further research and development of systems in which versatile and stable advanced functions can be achieved in a scalable manner is essential.

5 Summary

In the near future, large-capacity networks using an optical technology, called WDM lightpath networks, will be constructed. Traffic volume in networks will undoubtedly continue to grow for years to come, and WDM lightpath networks may eventually be unable to meet this demand. At that time, the fundamental methods of building a network will be reexamined. Photonic packet-switched networks are suitable for these needs.

In this paper, we have presented an overview of our proposed multi-wavelength label network. This network is a concrete example of photonic packet switching. To implement this architecture into network backbones, current networks must be expanded and improved to provide large capacity, high throughput, and advanced functions. We enumerate the problems involved in such a proposal, including issues involving network architecture, efficient contention resolution, efficiency improvements, reliability, advanced functionality, and network migration, and present several directions for future research on these topics.

References

1 B. Mukherjee, *"WDM-based local lightwave networks Part I:Single-hop systems"*, IEEE Network, Vol. 6, No. 3, pp.12-27, May, 1992.

2 N. Ghani, S. Dixit, and T. Wang, *"On IP-over-WDM integration"*, IEEE Communications Magazine, Vol.38, No.3, pp.72-94, Mar., 2000.

3 I. Chlamtac, A. Ganz, and G. Karmi, *"Lightpath Communications: An approach to high bandwidth optical WAN's"*, IEEE Transactions on Communications, Vol. 40, pp. 1171-1182, Jul., 1992.

4 B. Mukherjee, D. Banerjee, S. Ramamurthy, and A. Mekherjee, *"Some principles for designing a wide-area WDM optical network"*, IEEE/ACM Transactions on Networking, Vol. 4, No. 5, pp. 684-696, Oct., 1996.

5 N. Wada, H. Harai, W. Chujo, and F. Kubota, *"Photonic packet routing based on multi-wavelength label switch using fiber Bragg gratings"*, ECOC2000, Vol.4, No.10.4.6, pp.71-72, Sep., 2000.

6 N. Wada, H. Harai, W. Chujo, and F. Kubota, *"PHOTONIC NETWORK BASED ON MULTI-WAVELENGTH LABEL SWITCH"*, IEICE PNI Workshop (PNI2000-24), pp.45-51, Oct., 2000 (in Japanese).

7 H. Harai, N. Wada, F. Kubota, and W. Chujo, *"A SWITCHING NODE ARCHITECTURE FOR MULTI-RATE PATH ESTABLISHMENT IN MULTI-WAVELENGTH LABEL SWITCHING NETWORKS"*, IEICE Technical Report (PS2000-37), Dec., 2000 (in Japanese).

8 H. Harai, N. Wada, F. Kubota, and W. Chujo, *"A STUDY ON PHOTONIC SWITCHING NETWORK WITH PHOTONIC ADDRESS PROCESSING"*, Proceedings of the 2001 IEICE General Conference, SB-

10-2, pp. 745-746, Mar., 2001 (in Japanese).

9 S. Araki, S. Takahashi, Y. Maeno, Y. Suemura, A. Tajima, H. Takahashi, K. Matsuda, T. Tamanuki, S. Dohmae, and N. Henmi, *"A 2.56 Tb/s throughput packet/cell-based optical switch-fabric demonstrator"*, ECOC '98, pp.127-128, 1998.

10 Y. Suemura et.al, *"TERABIT/S OPTO-ELECTRONIC PACKET SWITCH DEMONSTRATOR"*, IEICE Technical Report (PS99-55), Dec., 1999 (in Japanese).

11 K. Habara, H. Sanjo, H. Nishizawa, Y. Yamada, S. Hino, I. Ogawa, and Y. Suzaki, *"Large-capacity photonic packet switch prototype using wavelength routing techniques"*, IEICE Transactions on Communications, Vol. E83-B, No.10, pp.2304-2311, Oct., 2000.

12 D.K. Hunter et.al, *"WASPNET: A wavelength switched packet network"*, IEEE Communications Magazine, Vol. 37, No. 3, pp.120-129, Mar., 1999.

13 D.K. Hunter and I. Andonovic, *"Approaches to Optical Internet packet switching"*, IEEE Communications Magazine, Vol.38, No.9, pp.116-122, Sep., 2000.

14 S. Yao, B. Mukherjee, and S. Dixit, *"Advances in photonic packet switching: An overview"*, IEEE Communications Magazine, Vol.38, No.2, pp.84-94, Feb., 2000.

15 E. Modiano, *"WDM-based packet networks"*, IEEE Communications Magazine, Vol.37, No.3, pp.130-135, Mar., 1999.

16 S. Nojima, *"TECHNOLOGIES FOR HIGH SPEED ROUTER AND PROBLEMS"*, IEICE PNI Workshop (PNI99-5), pp. 29-34, Jun., 1999 (in Japanese).

17 D. Awduche, Y. Rekhter, J. Drake, and R. Coltun, *"Multi-protocol lambda switching: Combining MPLS traffic engineering control with optical crossconnects (draft-awduche-mpls-te-optical-02.txt)"*, IETF Internet Draft (Work in Progress), Jul., 2000.

18 H. Takara, T. Ohara, K. Mori, K. Sato, E. Yamada, K. Jinguji, Y. Inoue, T. Shibata, T. Morioka, and K-I. Sato, *"Over 1000 Channel Optical Frequency Chain Generation from A Single Supercontinuum Source with 12.5GHz Channel Spacing for DWDM and Frequency Standards"*, ECOC 2000 Post Deadline Paper, Sep., 2000.

19 M. Murata et al, *"IP over a-thousand-wavelength division multiplexing: Is it useful and possible for resolving the network bottlenecks?"*, IEICE Technical Report (SSE99-170), pp. 55-60, Mar., 2000.

20 H. Harai, F. Kubota, and H. Nakazato, *"Design of reconfigurable lightpaths in IP over WDM networks"*, IEICE Transactions on Communications, Vol. E83-B, No. 10, pp. 2234-2244, Oct., 2000.

21 H. Harai and F. Kubota, *"Bandwidth maximization in IP over WDM path networks"*, Proceedings of SPIE OptiComm 2000, pp. 9-20, Oct., 2000.

22 S. Arakawa, M. Murata, and H. Miyahara, *"DESIGN OF LIGHTPATH NETWORKS WITH PROTECTIONS FOR IP OVER WDM NETWORKS"*, IEICE Technical Report (SSE99-111), Dec., 1999 (in Japanese).

23 K. Kitayama and N. Wada, *"Photonic IP Routing"*, IEEE Photon. Technol. Lett., Vol.11, p.1689, 1999.

24 N. Wada and K. Kitayama, *"Photonic IP routing using optical codes: 10Gbit/s optical packet transfer experiment"*, OFC2000, WM51, p.362, 2000.

25 D.K. Hunter et. al., *"Buffering in optical packet switches"*, IEEE/OSA Journal of Lightwave Technology, Vol. 16, pp. 2081-2094, Dec., 1998.

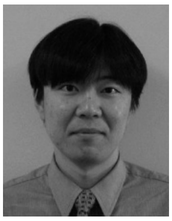
26 X. Wang, H. Morikawa, and T. Aoyama, *"Burst optical deflection routing protocol for wavelength routing WDM networks"*, Proceedings of SPIE Opticomm 2000, pp.257-266, Oct., 2000.

27 S. Yao, B. Mukherjee, S.J.B. Yoo, and S. Dixit, *"All-optical packet-switched networks: A study of contention-resolution schemes in an irregular mesh network with variable-sized packets"*, Proceedings of SPIE OptiComm 2000, pp. 235-246, Oct., 2000.

28 A. Watanabe and S. Okamoto, *"AN IMPLEMENTATION OF A FAULT/DEGRADATION IDENTIFICATION MECHANISM FOR REALIZING ROBUST WDM OPTICAL PATH-BASED PHOTONIC TRANSPORT NETWORKS"*, IEICE Technical Report (SSE99-152), pp.37-42, Feb., 2000 (in Japanese).

29 F.Kubota et al., *"Implementation and evaluation of active internetwork system using Stream Code based active network"*, Proceedings IEEE 15th International Conference on Information Networking (ICOIN-15), pp.232-239, Jan., 2001.

30 F.Kubota et al., *"Congestion management based on routing functions over active internetwork system"*, Technical Proceedings 2000 Asia-Pacific Network Operations and Management Symposium (APNOMS2000), pp.91-102, Oct., 2000.



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