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Optical Packet & Circuit Integrated Network for Future Networks

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SUMMARY This paper presents recent progress made in the development of an optical packet and circuit integrated network. From the viewpoint of end users, this is a single network that provides both high-speed, inexpensive services and deterministic-delay, low-data-loss services according to the users' usage scenario. From the viewpoint of network service providers, this network provides large switching capacity with low energy requirements, high flexibility, and efficient resource utilization with a simple control mechanism. The network we describe here will contribute to diversification of services, enhanced functional flexibility, and efficient energy consumption, which are included in the twelve design goals of Future Networks announced by ITU-T (International Telecommunication Union - Telecommunication Standardization Sector). We examine the waveband-based network architecture of the optical packet and circuit integrated network. Use of multi-wavelength optical packet increases the switch throughput while minimizing energy consumption. A rank accounting method provides a solution to the problem of inter-domain signaling for end-to-end lightpath establishment. Moving boundary control for packet and circuit services makes for efficient resource utilization. We also describe related advanced technologies such as waveband switching, elastic lightpaths, automatic locator numbering assignment, and biologically-inspired control of optical integrated network.
key words: *new generation network, optical packet switching, optical circuit switching, moving boundary*

1. Introduction

The Internet is a key part of today's social infrastructures, and its importance will continue to grow. However, in viewing the complex process of technological expansion of the Internet, questions will arise about whether it will contribute to solving diverse social problems, or whether it will become an infrastructure for creating a new philosophy for enhancing quality of life and productivity. The so-called new-generation network (NWGN) has been envisioned as a replacement for the Internet to solve the above questions [1], and research and development (R&D) is currently underway to realize the NWGN, or more generally, Future Networks [2]–[4].

In this paper, we describe the R&D of an optical packet and circuit switched network and related technologies. These are technologies that will solve the issues related to the diversification of services, enhanced functional flexibility, and efficient energy consumption with high-switching capacity as network traffic will increase in the future.

This paper is organized as follows. In Sect. 2, we describe the motivation for integrating optics in the NWGN. In Sects. 3 and 4, we examine optical packet and circuit integrated network technology and related advanced technologies, respectively. Finally, we make some concluding remarks in Sect. 5.

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2. Motivation for Integrating Optics in the NWGN

In the future, humans will create a new philosophy for enhancing quality of life and the productivity. It is thus natural that the requirements of both people and applications will be diversified. For example, there are currently web server-client systems and peer-to-peer (P2P) systems. In Japan, due to the P2P-traffic reduction control by Internet service provider (ISP), data distribution between subscribers and content servers, such as YouTube is increasing. It has been estimated that, in our future society, there will be as many as one trillion wireless devices and sensors each generating a small amount of traffic [5]. Such data will be transferred mainly via best-effort data services.

On the other hand, there are some applications where the data communication bandwidth is insufficient when using best-effort service, including high-resolution video, remote surgery, and e-Science. In the present-day Internet, a large volume of traffic from a small number of users causes adverse effects on the communication quality experienced by other users. Thus, the network should also provide a deterministic-bandwidth end-to-end circuit to users requesting high-quality data transfer services. By splitting data on the network into data for packet-switched services and data for circuit-switched services, the network can maintain a required level of satisfaction for all network users.

The NWGN will provide diversified network services by building such a packet and circuit integrated network where packet switching and circuit switching are accommodated on a single network service. In the NWGN, web data and sensor data are transferred via best-effort-based packet switching. If best effort is not good enough because of quality degradation, the application data is transferred on an end-to-end circuit. Figure 1 shows an overview of the service.

As applications on the Internet become more diversified, the volume of Internet traffic is increasing continuously [6]. This mainly stems from the higher speed of subscriber lines, such as asymmetric digital subscriber lines (ADSL) and fiber-to-the-home (FTTH). When we look at wireless access, the number of WiMAX (Worldwide Interoperability for Microwave Access) subscribers is increasing, and wireless network traffic will increase. The bandwidth of mo-

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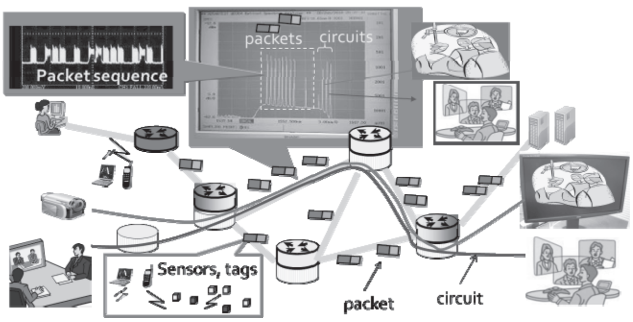

Fig. 1 Overview of packet and circuit service.

bile terminals will also increase from 3G to long term evolution (LTE), and LTE Advanced. Global mobile data traffic is growing by a compound average growth rate (CAGR) of 0.92 [7]. We should improve energy efficiency in the whole of the networks such that energy consumption is not linearly related to the amount of traffic. One straightforward idea is to replace packet switching with circuit switching in part. The power consumption for packet switching is given by an increasing function of line rate because the number of packets handled increases according to the line rate, in contrast to circuit switching, which does not [8]. The energy efficiency of electronic circuitry is constantly improving, and many of the devices used for accessing networks have sleep-mode function. However, it is difficult to introduce sleep-mode functions in the core network where data is concentrated. Thus, it is natural to reduce the amount of electronic circuitry and install optical technologies for energy saving. With this approach, packets and circuits are optically switched in the core. This will achieve a tremendous increase in switching capacity and higher energy efficiency.

Moreover, the packet and circuit integrated network will contribute to simplification of network facilities and network operation. Individual networks, each having unique network characteristics corresponding to the service requirements, are unified into a packet-based IP network. As can be understood from the historical background, building many individual service-oriented networks is not enough from the viewpoints of facility investment, operational efficiency, and user convenience. Virtualization technology is promising for aggregating network resources operated by multiple infrastructure service providers. Although it is an effective approach for optimization of given resources, packet and circuit resources in the equipment itself is not optimized. Each provider using the integrated network can further optimize resources while maintaining simplicity.

In short, a desired optical packet and circuit integrated network has the following features. From the viewpoint of end users, this is a single network providing high-speed, inexpensive services and deterministic-delay, low-data-loss services according to the users' diverse usage scenarios. From the viewpoint of network service providers, it is a network that provides large data-switching capacity with low energy consumption, high flexibility, and efficient resource utilization as well as a simple control mechanism.

3. Optical Packet and Circuit Integrated Networks

3.1 Waveband-Based Network Structure

A fast path to practical realization of an optical integrated network by 2020 is to adopt mature dense wavelength division multiplexing (DWDM) technologies in transmission and cross-connection. Thus, the maintenance units for the network are hierarchical: a *wavelength channel* grid compliant with ITU-T G.692 and *waveband,* which is a bundle of wavelengths consisting of a fixed number of wavelengths. To users who want guaranteed bandwidth, the network provides a single wavelength from a source node to a destination node. To users who want traditional best-effort service, the network provides a much higher-speed service than today's Internet by using optical packet switching in the core. Namely, the service boundary is a waveband and each waveband is used for either circuit switching or packet switching. By increasing and decreasing the number of wavebands as necessary, we can operate the optical network efficiently. Since an optical packet here consists of the whole waveband, the ability of erbium-doped fiber amplifiers (EDFAs) to amplify the whole waveband with a single device is fully utilized. Thus, the network can provide broadband communication.

Optical packet switching is a switching technology where optical signals of payload data are not converted into electrical signals at the switching point, and each packet is individually switched in packet communication in the optical domain. We developed an optical switching technology where each optical packet consists of multiple wavelengths for speeding up packet transfer, and packets are switched by optical switches according to the information in the packet header [9]–[11]. Figure 2 shows an example format of a multi-wavelength optical packet. Here notations "A" through "T" represent wavelengths constituting a packet (a 20-wavelength optical packet in this example). The header and payload of the packet may consist of multiple wavelengths. Each wavelength is a part of the packet. The bit-rate per wavelength is approximately 10 Gbps because optical-electrical (O/E) and electrical-optical (E/O) conversion technologies are mature at that rate. By transmitting 10 to 100 wavelengths in parallel and switching all wavelength packets by using a single switch, 100 Gbps to 1 Tbps optical packet switching is achieved. Dedicating some of the wavelengths to the header of the optical packet minimizes the number of optical-electrical conversions. Thus, optical packet switching is energy efficient [11]. In contrast, if we use electronic switching, the wavelengths must be demultiplexed and all wavelength signals must also be deserialized into multiple low-speed signals for electronic switching.

On the other hand, lightpaths are used as the communication medium for guaranteeing service quality on an end-to-end basis, and are generally provided on a single wavelength on an ITU-T G.692 grid. Applications that demand more than 10 Gbps bandwidth may be able to use multiple

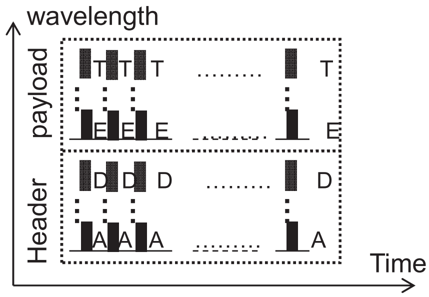

Fig. 2 Optical packet format.

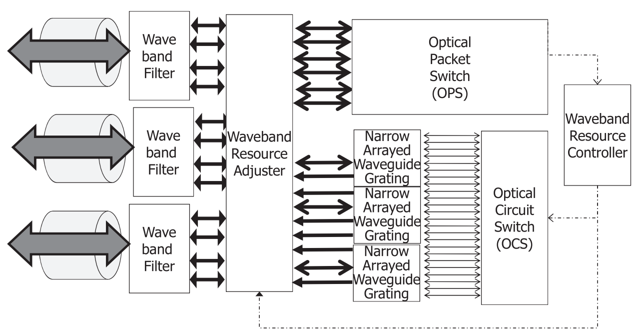

Fig. 3 An optical integrated node.

wavelengths [12]. In future, we will need an asymmetric lightpath setup where the numbers of upstream and downstream lightpaths differ. Server-client type high-resolution video transfer is a typical example of an asymmetric application.

Figure 1 also shows applicable areas for optical services and optical switching in the optical packet and circuit integrated networks. In areas in which data is concentrated, switching is handled in the optical domain. In this figure, the white optical packet switch (OPS; cylinder with arrows) has an optical switching function. The dark packet switch has an O/E/O conversion function, and the payload is switched in the electrical domain. Nodes that are a combination of white and dark colors have optical packet transceivers. A node that has both packet and circuit switching capabilities is a packet and circuit integrated node. Areas that do not need a line rate of more than 10 Gbps will adopt O/E/O switching nodes. Nodes in access areas meet this condition.

3.2 Optical Integrated Node Structure

Figure 3 shows a block diagram of an optical node in an optical network consisting of wavelength division and multiplexing technologies. To simplify the illustration, a pair of input and output fibers is shown by a single bi-directional arrow. Optical signals coming from external input optical fibers are demultiplexed into multiple wavebands at the waveband filters. The figure shows the case of three external input/output fibers and four wavebands per fiber. The frequency bandwidth of the waveband is determined by the communication system adopted. If 100 Gbps communication is needed by using existing 100 GHz-spacing wavelength multiplexers and demultiplexers, a configuration including 10 wavelengths each carrying 10 Gbps would be appropriate. The frequency bandwidth of the waveband is 1 THz in this case. A waveband resource adjustor is a module for switching optical signals to the appropriate switch block for each waveband. By monitoring the amount of traffic in packet switching and the number of lightpaths in the circuit switching, the adjuster determines the need for increasing or decreasing resources and appropriately adjusts resources to avoid congestion of either switching system. Waveband conversion [13] may be performed if necessary.

An OPS switches multi-wavelength optical packets consisting of wavelengths in the whole waveband. It receives optical packets such as control and management packets for lightpath establishment and release and those for packet networks and performs signaling, routing, and so on. The OPS counts the number of packets and lightpaths through the node by monitoring the headers of the packets and reports the result to the waveband resource controller. The resource controller drives the resource adjustor to adjust the amount of resources. Wavebands for lightpath services are further demultiplexed into individual wavelengths at multiple narrow-bands arrayed waveguide gratings (NAWGs), and each wavelength is switched appropriately at the optical circuit switch (OCS). For the NAWG, we use a cyclic AWG, which leverages the cyclic frequency property. Thus AWG devices with the same specifications can be used in different wavebands by performing temperature adjustment, allowing equipment costs to be reduced.

The switching capacity of an OCS handling eight-thousand 10 Gbps lightpaths is 80 Tbps. The switching capacity of an OPS having sixty-four 1.28 Tbps (10 Gbps times 128 wavelengths) lines [14] is also 80 Tbps. A combination of both technologies can realize an optical integrated node with a switching capacity of over 100 Tbps. A strictly non-blocking optical switch with 8,000 ports may consist of a three-stage Clos switch in which each switching element is a 256-port optical micro-electro-mechanical systems (MEMS) switch. The insertion loss of a state-of-the-art optical MEMS switch is around 5 dB. Therefore, the three-stage switch would produce a loss of only 15 dB and does not need any amplifiers at intermediate stages. This reduces the cost of the node.

3.3 Features of the Integrated Network

We now describe the features of this network from the viewpoints of service diversity, functional flexibility with a simple control structure, and energy consciousness with high transmission speed. These features will be important in the future. ITU-T Recommendation Y.3001 defines twelve design goals for Future Networks [15]. Service diversity, functional flexibility and power consumption are included in these goals.

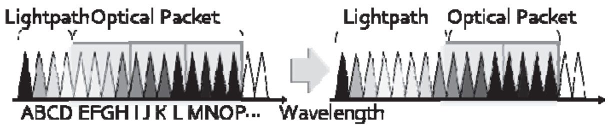

Fig. 4 Moving boundary for packet and circuit services.

A) Service diversity

- Provides diversified services from best effort to quality-guaranteed services.
- Provides application-level quality of service (QoS) and host-level QoS for end-to-end lightpath services.
- Provides a function that dynamically moves the boundary between resources for optical packet services and those for lightpath services in order to meet changing user needs. Figure 4 shows that all of the wavelengths in an optical fiber are shared with all services and the moving boundary control enables provision of flexible services to packet users and lightpath users. Before moving the boundary, one waveband is provided for up to four lightpaths and three wavebands in which three four-wavelength packets can be transferred in parallel are provided for packet services. After moving the boundary, two wavebands are provided for up to eight lightpaths and two wavebands are provided for packet services.

B) Functional flexibility with simple control

- Integrates a control block for optical packet switching and a control block for optical circuit switching. Traditionally the messages for controlling lightpaths are transferred via out-of-band networks. Our optical packet switching handles such messages. Thus, the controlled network is unified, which simplifies control and management. OpenFlow [16], [17] is a similar integration technology that integrates electronic packet switching and optical/electronic circuit switching. The optical switching technology in the present paper is a powerful tool at 10 Gbps or more and is promising for fusing high-speed, energy-conscious optical switching and sophisticated electronic switching.
- Handles packets with layer-3 header processing. Although we have not developed it yet, layer-3 header processing can be used. Current Internet operators must manage IP network and large-scale Ethernet services. Network management will be simplified by not using multiple layers.

C) Energy consciousness with high transmission speed

- Introduces optical switching into packet switching and integrates optical circuit switching that bypasses packet switching, which will achieve energy saving in the core.
- Forms optical packets of multiple wavelengths, each of which data rate is 10 Gbps, and uses a small portion of the wavelengths as headers. Only the header wavelengths are converted into electrical signals. The payload of the packet itself is not converted into electrical signals, and packets having multiple wavelengths are switched by a single optical switch. Restricting electrical conversion to only part of the packets, contributes to a large reduction in energy consumption.
- Omits unnecessary packet processing. For users who request extremely high quality and a bandwidth of 1 Gbps or more, a lightpath is provided for guaranteed quality and energy savings.

3.4 Optical Circuit Switching

This subsection addresses the control mechanism for optical circuit-switched networks that can guarantee service quality from end to end. Wavelength-switched optical networks (WSONs) have been standardized for transport core networks. The main standard targets in WSONs are OSPF-TE (open shortest path first — traffic engineering), PCE (path computation element), and RSVP-TE (resource reservation protocol — TE) for link-state dissemination, route calculation, and wavelength assignment, respectively. The mechanism of OSPF-TE is a distributed cooperative control, and that of PCE is a centralized control. For RSVP-TE, although intra-domain sequential lightpath assignment has been discussed extensively, inter-domain methods and simultaneous assignment methods are lacking. In the following, inter-domain QoS routing and lightpath assignment are mainly described.

Similar to a packet-switched network, the problem of determining the amount and class of control information to be advertised between neighboring domains arises. In packet-switched networks, only information about route reachability is disclosed. However, additional information will be required to guarantee QoS for lightpath establishment. Not only are domain administrators reluctant to disclose all control information, but since detailed information is also more troublesome to process at the receiving side, it is appropriate to use information that is abstracted to some degree.

If optical circuit switching does not have the constraint that the same wavelength must be assigned on each channel on the route, the signaling only has to tell whether or not the requested bandwidth in terms of bit-rate remains. However, to reserve wavelengths when setting lightpaths, free wavelengths must be obtained by probing wavelength-state information.

If an administrator prevents more than the required information from being disclosed and there are no free resources, there will be repeated attempts to establish a path, which will take time. In this case, the end user could feel dissatisfied. Nevertheless, domain administrators may not wish to notify neighboring domains of the availability of wavelengths that are not ultimately used.

To solve this problem, we have proposed a rank-accounting method where a limited amount of wavelength-state (i.e., idle or busy) information is correctly exchanged among multiple domains at signaling time, and up to K wavelengths that are likely to be idle are selected at the

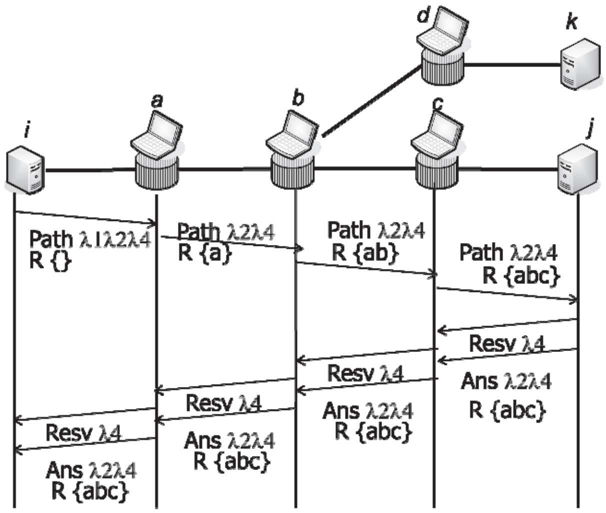

Fig. 5 Signaling in rank accounting method.

source node/domain from W multiplexed wavelengths [18], [19]. A rank for each wavelength and source-destination pair is calculated when a lightpath is established, and K wavelengths with higher ranks are selected and included in the Label Set Object of RSVP-TE's [20] Path message in lightpath establishment. RSVP-TE is extended by defining a new "Ans (Answer)" message toward the upstream side. As shown in Fig. 5, the message is used to report the latest available-wavelength information to the source node for rank updating and is generated at the destination node by copying Label Set Object in the Path message. If it is difficult to adopt the proposed new Ans message for some reason, an optional object of a Resv message can be used to include a Label Set Object.

The K wavelengths selected at the source node are updated. For wavelength x in the available wavelength group (wavelengths 2 and 4 in Fig. 5) between nodes i and j, rank $r_x(m_{ij})$ is updated with an exponential moving average, which can be implemented with a small record space, as follows

$$r_x(m_{ij}) = (1 - \alpha)r_x(m_{ij} - 1) + \alpha, \tag{1}$$

where α is a parameter in the interval [0,1]. For wavelength y in the not-available wavelength group (wavelength 1 in Fig. 5), on the other hand, rank $r_y(m_{ij})$ is updated as follows:

$$r_y(m_{ij}) = (1 - \alpha)r_y(m_{ij} - 1). \tag{2}$$

One may think that this collected information is too small and that ranking does not reflect the latest availability. We extended this rank accounting mechanism aggressively so that source nodes borrow available and not-available wavelength information whose source node is identical. The rank $r_x(m_{ik})$ for wavelength x from node i to k is updated when an attempt is made to establish a lightpath from node i to j and if x is included in the Ans message for nodes i to j:

$$r_x(m_{ik}) = (1 - \alpha\beta_{ijk})r_x(m_{ik} - 1) + \alpha\beta_{ijk},$$

where β_{ijk} is the accuracy index [18].

The rank accounting method is effective not only for lightpath establishment over multiple domains but also for simultaneous multi-lightpath establishment [19]. This is because the possibility of attempting to reserve the same wavelength for establishing multiple simultaneous paths is reduced.

3.5 Optical Packet Switching

This subsection addresses optical packet switching technologies for high-speed transmission and energy saving. The optical packet speed is around 100 Gbps. Details are described in [11].

We are unlikely to have mature optical random-access memory (RAM) by 2020. A feasible solution will be an optical fiber-delay-line buffer in which optical switches and optical fibers are used. It has been said that the physical size is critical. The size is much larger than semiconductor RAM but the maximum length can be reduced to 100 meters or less. The background is described here. Optical packet switching should be introduced for line speeds of 100 Gbps or higher, where electronic processing based on serial-to-parallel conversion consumes a large amount of energy. At that speed, the fiber length equivalent to 64 bytes is around 1 meter. When the average packet length is assumed to be 128 bytes, 35 fiber delay lines are enough to satisfy a packet loss probability 0.001 or less, which is recommended in Y.1541 at 50% link load. A maximum fiber length less than 100 meters is feasible from viewpoint of implementation.

We have been conducting R&D on optical packet switching. The previous system we developed was not suitable for bi-directional transmission, and therefore, some static routing configuration is necessary. With that system, we achieved data transmission using TCP/IP or UDP/IP over optical packets at a speed of 80 Gbps [9], [21]. Moreover, signaling packets for lightpath setup are transferred in optical packets and are terminated at the optical integrated nodes for integration [21]. We achieved 170 km optical packet transmission including optical switching and buffering where three fiber-delay lines are incorporated and lightpaths are multiplexed with other wavelengths in the same optical fiber [22]. Higher-speed switching and buffering will be described later.

3.6 Integrated Control and Management

A packet-switched network uses routing for reachability to data communication. In contrast, a circuit-switched network uses signaling for meeting user's QoS requirement and routing for reachability of signaling information and dissemination of QoS information. Since the philosophies of the two switching principles are mutually exclusive, we do not attempt to unify them directly.

Instead, we control and move the boundary between resources for packet services and those for circuit services.

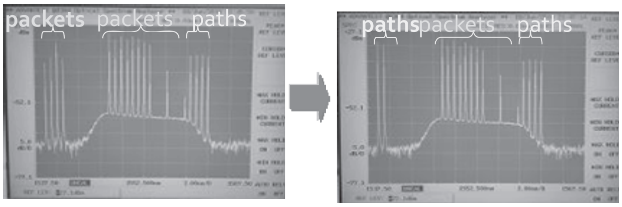

Fig. 6 Experimental moving boundary.

The boundary is moved according to the utilization of both services. For this purpose, we obtain the number of packets transferred and the number of lightpaths established at every node. We integrate the network by sharing optical packet line among packet data, packet control information, and circuit control information [21].

In order to operate the network even if the available resources change dynamically, we extend the previous circuit switching implementation described in Sect. 3.4 to a dynamic change of resources for circuit switching. Namely, the network system is made robust against change of link resources.

Figure 6 shows wavelength spectra before and after the boundary moves when the number of lightpaths on a link reaches the predetermined threshold. The network replaces a waveband used for packet services with that user for circuit services. Before moving, two wavebands are allocated to packet switching services (but the numbers of wavelengths forming optical packets are different from each other because of our limited hardware facilities). As the number of lightpaths increases and reaches the predetermined threshold, one of the packet wavebands is changed into a circuit one. It took 500 ms or less for the boundary change and lightpath establishment/release [23].

3.7 Testbed Technology

The National Institute of Information and Communications Technology (NICT) has developed the first practical-level optical packet and circuit integrated node [24]. In the packet section, the node has an OPS, an optical packet generator, and an optical packet receiver. This is a fusion of previously developed technologies such as optical burst-mode receivers and amplifiers. This improves the performance of optical packet switching systems. The packet error rate (PER) at each receiver is less than 10^{-4}, which meets PER requirements for high-quality IP network services stipulated in ITU-T Recommendation Y.1541 [25]. We expect that this node will be introduced into an R&D network testbed such as JGN-X for building a prototype NWGN.

In the header of the optical packet, a label is defined and is used for routing information in the optical network only. An optical packet generator matches the destination address of an IPv4 packet from an access network to a predetermined x-bit ($1 \leq x \leq 32$) pattern with a predetermined offset recorded in the lookup table. It then generates an optical packet with a proper label. The payload of the optical packet contains the whole variable-length IP packet from the access network. An optical packet receiver can reassemble the IP packet again. Since IP packets and optical packets are in one-to-one correspondence, transparent and low-delay data transmission is achieved.

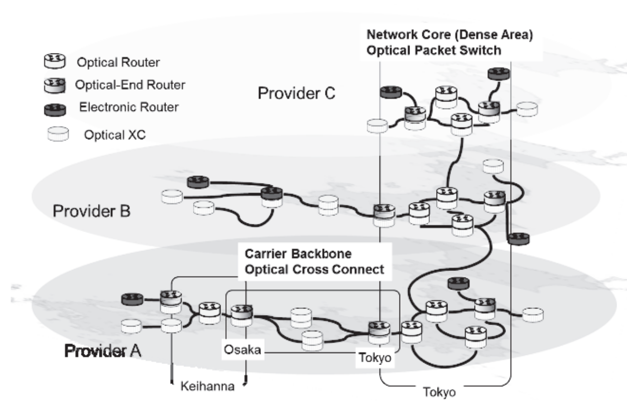

Fig. 7 Applied areas of each switching method and optical technologies.

3.8 Applied Area of the Optical Technologies

We have stated above that nodes on which traffic is concentrated should be switched in the optical domain. We show details here. Figure 7 shows applied areas of packet switching and circuit switching and applied areas of optical packet switching and electronic packet switching. Routers (i.e., packet switching nodes) are installed in the border of a domain (i.e., a network service provider) in the current Internet. A change to the inter-domain connection paradigm, namely, replacing the packet-switching paradigm with a circuit-switching one and then doing packet-over-circuit type traffic-engineering over multiple domains is difficult. Thus, as shown in Fig. 7, optical packet switching is performed by installing an optical integrated node at a border or internal point of a domain where a large volume of traffic is incoming or outgoing and a packet switching service is operated currently. In parallel, the optical circuit switching function of the optical integrated node is used for an end-to-end lightpath service. Like this, optical packet switching is used for high-speed packet switching in the core through which many packets flow. The candidate locations in Japan are metropolitan areas such as Tokyo or Kansai.

On the other hand, we have not yet confirmed packet switching over long-distance (500 km or more, e.g., from Tokyo to Osaka in Japan), where we have to look at optical signal degradation due to signal distortion. However, similar to internal traffic exchange in metropolitan area, there is much traffic between the two metropolitan networks. In this case, in a single domain, optical packets may be changed into electronic signals and then mapped into OTN3 (Optical Transport Network) or OTN4 frames. Namely, from the point of view of the long-distance "backbone", data is transferred in the form of packets over a circuit. This is not optimization by multiple layers. The packet switching is an application of long-distance circuit-switched networks.

4. Related Advanced Technologies

4.1 Waveband Switching

As described in Sect. 3, for each waveband, in other words, a set of a fixed number of wavelengths, an optical packet service or an optical circuit service is provided. Since the capacity of a single wavelength here is 10 Gbps, to realize a node with a throughput of 100 Tbps in circuit switching requires a 10,000-port optical switch or a multi-stage structure as described previously. To decrease the size of the optical switch, Sato proposed a multi-layer switching architecture and an efficient lightpath accommodation method for the architecture [26]. In their proposed system, a two-layer node consisting of waveband switching and wavelength switching functions is used. A hierarchical structure taking into account a colorless, directionless reconfigurable optical add/drop multiplexer (ROADM) has also been studied [27].

The previous multi-layer network assumed that all lightpaths are preplanned. On the other hand, such preplanning is not always accurate; namely, unpredictable, dynamic (e.g., random service duration) lightpath requests may occur in future. Making guidelines for establishing and releasing waveband paths in response to dynamic wavelength path requests will be more important.

4.2 Elastic Lightpaths

In packet switching, data from multiple sources share a single channel. Since the optical-packet rate (e.g., 100 Gbps) is much faster than the subscriber line rate (e.g., 100 Mbps for FTTH, 11 Mbps for WiFi (Wireless Fidelity)), the data from each source looks to be very small and arrives randomly. Thus, efficient channel usage is expected. On the other hand, when a network assigns a dedicated bandwidth to a single user for a high-quality service, providing a wavelength from among the available WDM wavelengths is the most mature method. However, the frequency interval of WDM is fixed and predetermined. Even if a user wants 1 Gbps, WSON has to provide a frequency bandwidth equivalent to other 10 Gbps services. This is not efficient from the viewpoint of resource utilization.

Recently, advancements have been made in elastic optical communication technology by the use of optical orthogonal frequency division multiplexing (OFDM) [28]. Optical OFDM is a subcarrier multiplexing technique that is tolerant to chromatic dispersion and polarization mode dispersion. The elastic feature makes the frequency band efficient and is suitable for optical cross-connect based optical circuit switching. Consequently, partial and gradual migration from WDM-based, deterministic bit-rate service to optical OFDM-based, multi-granular bit-rate service is a promising scenario. With this approach, finer granular end-to-end bandwidth guaranteed service can be provided.

4.3 Optical Switching and Buffering of Tera bps-Class Packets

The optical packet and circuit integrated network described in Sect. 3 incorporated 80 Gbps (8 wavelengths × 10 Gbps) or 100 Gbps (10 wavelengths) optical packet switching functions. We can increase the switching capacity by including the following outcomes, which were verified using pseudo-random signals for generating optical packets.

- 1.28 Tbps (128 wavelengths × 10 Gbps) optical packet switching using polarization independent optical switches [14].
- 640 Gbps (64 wavelengths × 10 Gbps) optical packet switching and buffering [10].

As for the optical buffer, three fiber-delay lines were confirmed to be operating in the optical integrated node. In addition, we developed an 8-port buffer management board for asynchronous, variable-length optical packets: it works at 200 MHz (i.e., 200 million packets per second (Mpps)), which is equivalent to a line speed of 100 Gbps for 64-byte packets [29]. The calculation architecture is based on a parallel and pipelined processing structure in which the time complexity for each processor is O(1) [30]. The simulation results were reported in [30], and the implementation showed that 80 Mpps per port and 200 Mpps per port operation was feasible with a 0.22 μm field programmable gate array (FPGA) and a 65 nm FPGA, respectively.

4.4 Locator Numbering

In order to reduce lookup time (or from another point of view, to increase the lookup throughput) and energy consumption, reducing the number of entries in the forwarding table of the node is a promising approach. The small size of the forwarding table is suitable for header processing in the optical packet switching [31]. We first describe the current situation regarding the forwarding table size, followed by ways of reducing the size. Our approach involves a hierarchical and automatic numbering assignment for locators. Here the locator is a location indicator used in layer 3 of the OSI reference model. An IP address is a locator on the Internet.

- The current Internet adopts provider-independent (PI) locator structure where locator aggregation is not easy. The number of entries in the forwarding table obtained from the border gateway protocol (BGP) is still increasing. A forwarding table consists of almost 380,000 entries in some autonomous system (AS) for IPv4 packet forwarding as of the end of July 2011 [32]. If the current rate of growth continues, 1 million entries will be registered by 2020.
- Introducing a provider aggregatable (PA) locator structure like early IPv6. The number of routing entries is

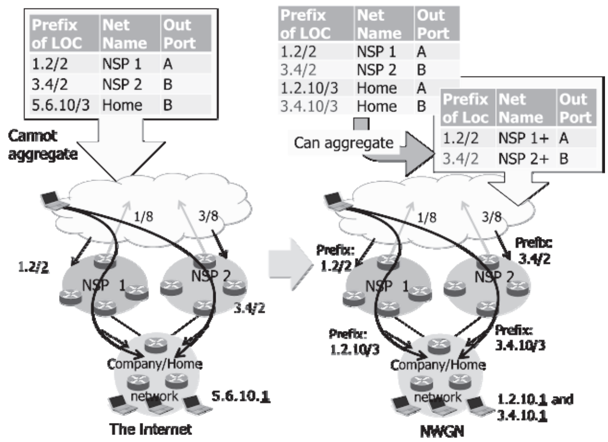

Fig. 8 Comparison of PI type Internet and PA type NWGN locator assignment.

reduced to the order of tens of thousands. Figure 8 compares the PI structure and the PA one when a site connects two parent domains. For simplicity of the illustration, we use IPv4's dotted-decimal notations with a slight modification. A locator consists of 4 numbers (e.g., 3.4.10.1 at the bottom right). For example, 3.4/2 shows that the first two numbers (3 and 4) form a prefix of the locator (3.4). In the right side of the figure, the prefix for the bottom company/home network is given hierarchical prefixes 1.2.10/3 and 3.4.10/3 from the above multihomed NSP1 (1.2/2) and NSP2 (3.4/2). While PI cannot reduce the forwarding table, PA reduces it by aggregating the prefixes. At the upper right of Fig. 8, NSP1+ includes NSP1 and the downstream network. The PA structure will directly contribute to a reduction of routing convergence-time, as well as increased lookup throughput and reduced energy consumption. For example, more than 80% of ASs do not have a child AS so if their locators are given by the parent AS, the routing table size can be reduced dramatically.

- Introducing an automatic number assignment mechanism that assigns locators to routers and end-hosts automatically. In the current Internet, a locator of an end-host can be assigned by using the dynamic host configuration protocol (DHCP) but the network prefix should be set in advance. Locators of routers are not assigned automatically. By automatically assigning locators, we can achieve a reduction in operating costs and an increase in availability resulting from a reduction in human configuration errors. Fujikawa et al. proposed hierarchical and automatic number assignment for locators [33]. When multi-homing is applied to the PA structure for reliability and traffic engineering, each node has multiple locators whose number is equivalent to the number of parent domains. Thus, automation is essential.
- Simplifying layer 3 operation by automation. Attempt to implement layer degeneracy of current similar operations and managements at layer 3 and layer 2.

If this approach works well, the number of bits and entries in the forwarding table will be reduced. This merit will compensate for the problems of optical packet switching mentioned above. Namely, the number of optical-to-electrical conversions of optical headers and the memory size for the lookup table will be reduced. Thus hierarchical locator numbering will contribute to building a simple, energy-conscious network [33].

4.5 Advanced Control for Integrated Network

In Sect. 3.6, we described a mechanism that moves the boundary between optical packet resources and optical circuit ones dynamically. However, the problem of the optimum timing for this movement has not been solved, and only a threshold-based mechanism has been implemented. Arakawa et al. proposed a biologically-inspired wavelength allocation method that allocates wavelengths to packet and circuit integrated networks [34]. Their method is based on a biological symbiosis model that explains co-existing and co-working types of bacterial strains in biological systems. They showed that biologically-inspired wavelength allocation achieves a nearly 40% reduction in latency compared with a threshold-based dynamic wavelength allocation method. Although the evaluation conditions were not the same as our designed optical packet and circuit integrated network (e.g., the packet bandwidth), this mechanism has the potential to optimize resource utilization with performance improvements from the user side.

5. Concluding Remarks

We have described the recent progress made in the development of an optical packet and circuit switching network. This is a waveband-based network architecture where packet and circuit resources are shared in units of waveband and the boundary is moved appropriately. Multi-wavelength optical packet have increased switching throughput with low energy: with state-of-the-art optical technology, they can be switched at a rate of 1.28 Tbps. A rank accounting method that uses local information via signaling provides a solution to the problem of an inter-domain signaling. We also described related advanced technologies such as waveband switching, elastic lightpath, automatic locator numbering assignment, and biologically-inspired control for optical integrated networks.

In the last 10 years, there have been advancements in many control and switching technologies for optical networking. When an optical packet and circuit switching network is developed by combining the component technologies described in this paper, the network will contribute to diversification of services, improved functional flexibility, and lower energy consumption, which are key design goals of Future Networks.

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