Optical Packet and Circuit Integrated Networks

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Toward deployment to the core in the New-Generation Networks where service diversity and high-speed, high-energy-efficiency are required, we develop optical packet and circuit integrated networks. We present 100 Gbps optical packet and circuit integrated nodes, Internet-access capable optical network testbed, and extension to SDN.

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, the questions arise as to whether it will contribute to solving diverse social problems, and 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), or more generally, the Future Networks (FNs) defined in ITU-T has been envisioned as a replacement for the Internet to solve the above questions[1][2], and research and development (R&D) is currently underway to realize NWGN as described in the special issue.

Our R&D is devoted to optical packet and circuit integrated network (OPCInet) (Fig. 1) and its optical packet and circuit integrated node (OPCI node) (Fig. 2) that provide diversification of services, enhanced functional flexibility, and efficient energy consumption[3]–[5], which contributes to Future Network vision recommended by ITU-T Y.3001[2]. OPCInet provides both high-speed, inexpensive services and low-delay, low-data-loss services according to the users' usage scenarios, from the viewpoint of end users. From the viewpoint of network service providers, this network provides large switching capacity with low energy consumption, high flexibility, and efficient resource utilization with a simple control mechanism.

In this paper, we present the overview of R&D of OPCInet and the following outcomes.

- Development of OPCI nodes
- Development of the OPCInet testbed and deployment to Internet access line
- Increase in the capacity of network testbed
- SDN (Software Defined Networking) extension
- Other enabling technologies such as optical buffer and address lookup

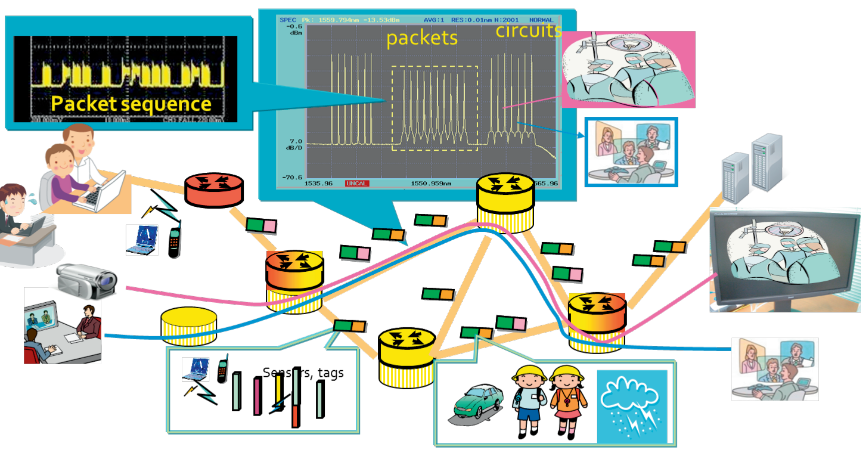


Fig. 1 An optical packet and circuit integrated network

Fig. 2 Photo of optical packet and circuit integrated node equipment

2 Service diversification and energy efficiency requirement

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 such as YouTube for video content download and peer-to-peer (P2P) systems. As contents on the Internet become more enhanced and then convenience of the Internet is improved, the volume of Internet traffic from home and corporation is increasing continuously. This mainly stems from the higher speed of subscriber lines, such as 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 mobile terminals will also increase from 3G to long term evolution (LTE), and LTE Advanced. 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. 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 such as high-resolution video, remote surgery, and e-Science. In the current 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 service is not good enough in quality, the application data can be transferred on an end-to-end circuit.

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. 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. As functions by traditional specific hardware appliances are being provided by software on network function virtualization (NFV), conducting resource efficiency of the network is a must for network infrastructure provider business. Moreover, using software-defined networking technology in the optical networks leads to efficient operation of the networks.

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

The OPCInet is featured by user and operator advantages described in Section **2**. Optical packet switching is an optical switching technology and method where data portion of an optical packet is switched in the optical domain with no electric conversion at intermediate nodes. We develop technology where an optical packet consisting

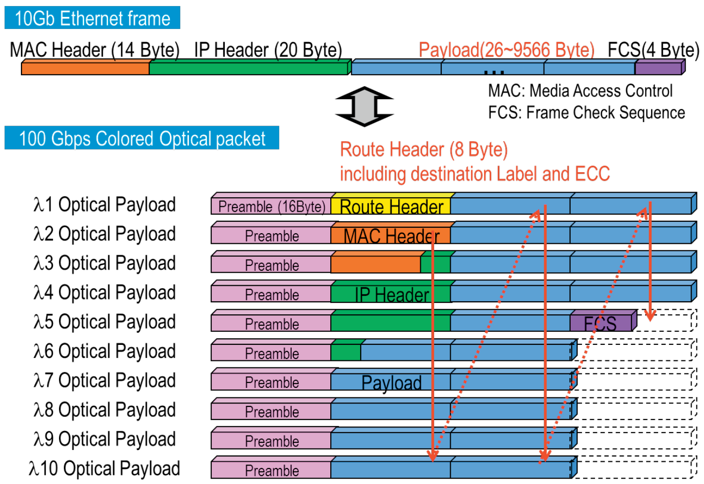


Fig. 3 Optical packet format

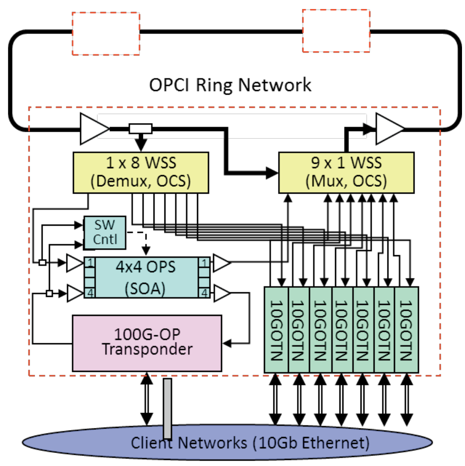


Fig. 4 Optical node architecture

of multiple wavelengths (i.e., total speed is multiplied by the number of wavelengths) is optically switched according to the information of the header of the optical packet. Figure 3 shows a simple representation of an Ethernet frame and an optical packet format consisting of 10 wavelengths. A wavelength of the optical packet is 10 Gbps where O/E and E/O technologies are matured. By multiplexing 10 to 100 wavelengths and combining other multiplexing technologies such as polarization multiplexing, 100 Gbps to 12.8 Tbps optical packet switching is achieved[3][6]. On the other hand, lightpath is a medium for guaranteeing service quality from end to end, and is provided by a wavelength in densely multiplexed wavelengths. An application which wants more than 10 Gbps bandwidths can use multiple lightpaths simultaneously.

We show OPCInet overview in Fig. 1. Switching in the core, data intensive area of the network is processed by optical technology. In this figure, yellow packet switches (cylinders with arrows) have optical packet switching capability; brown ones have electronic packet switching capability, and yellow with brown ones have optical packet transceiver capability. A node having packet switching capability and circuit switching capability is a packet and circuit integrated node.

We summarize our developed OPCInet based on OPCI nodes (see Figs. 2 and 4)[7][8].

- Mesh-type topology is a general structure. We implemented OPCI nodes capable of forming a single-ring and a multi-ring network.
- Optics is introduced in the packet switching and optical circuit switching that bypasses per-packet processing is integrated with optical packet switching at nodes. The optical packet switching and optical circuit switching make core of the network energy-efficient. One example is to make header processing of packet switching energy-efficient. We make an optical packet by using 10 wavelengths each of which bit rate is 10 Gbps and only one wavelength of them as a header. O/E conversion is applied the wavelength for header only. All the wavelengths forming an optical packet itself are switched by using a single optical switch. Limiting conversion to electric signals to a part of optical packets is contributed to the steep reduction of power consumption. In parallel, for the users who require quality and 1 Gbps or more bandwidth, lightpath by the use of optical circuit switching is provided for guaranteeing quality and saving energy.
- OPCInet uses 40 wavelengths of which intervals are 100 GHz in C band. Unit waveband consists of 10 wavelengths. Each waveband is either optical packet switching or optical circuit switching. Wavelength selective switch (WSS) in the OPCI node (de) multiplexes optical packet signals and optical circuit signals. The number of wavebands for each switching can be changed dynamically according to the volume of the services. Each lightpath (optical circuit) is switched to different port of WSS and 10 wavelengths forming optical packets are switched to a single port of the WSS.
- For optical packet switching, only a wavelength including header of the optical packets is changed into electric signals for electronic header processing such as address lookup. An OPS has 4 inputs and 4 outputs. 1 of the 4 ports is connected to the optical packet transponder that converts 10Gb Ethernet

frames to 100 Gbps optical packets and vice versa. Switching table consisting of entries representing destination address of incoming optical packet and switched output port of 4 × 4 OPS and lookup table showing relation between destination IP address and destination optical node address are configured via command from an external device.

- Lightpaths are setup and released by configuring WSS via distributed signaling. For this purpose, we developed an OSPF-TE/RSVP-TE based distributed control and management system[9][10]. A centralized SDN control is alternative way.

4 R&D outcome

4.1 Development of OPCI nodes

We developed a world-first optical packet and circuit integrated node equipment, which is shown in Figs. 2 and 4. The OPCI node consists of components mounted in 2 of 19-inch racks. In OCS links, an OTU2e transponder encapsulates 10GBASE-LR Ethernet frames from the client side into OTU2e format. A wavelength that is different from wavelengths for OPS is given to the OTU2e signal. Because optical paths are established by control packets in advance, there is no need to read the IP destination address of incoming 10GbE frames. In OPS links, on the other hand, a 100G-OP transponder encapsulates incoming 10GBASE-LR Ethernet frames from the client side into 100 Gbps colored optical packets.

Functional overview was described in Section **3**. Optical packet signals are bursty. Intensity of multiplexed lightpaths dynamically changes if multiple wavelengths are set or released in a short period of time. We dramatically improved optical receiver signal quality by embedding optical burst-mode amplifiers[11], which are tolerable to steep change of optical signal intensity, and optical burst-mode receivers that are capable of clock and data recovery of burst signals. Table 1 shows packet error rate (PER) of 2 or 3 hop optical packets received at optical packet transponders. The lengths of transferred Ethernet frames were 64, 1,518, and 9,000. The monitored PER is 10^{-4} or less, regulated as a high quality in ITU-T Y.1541. Figure 5 shows packet waveform of optical packet signals and optical circuit signals in our system.

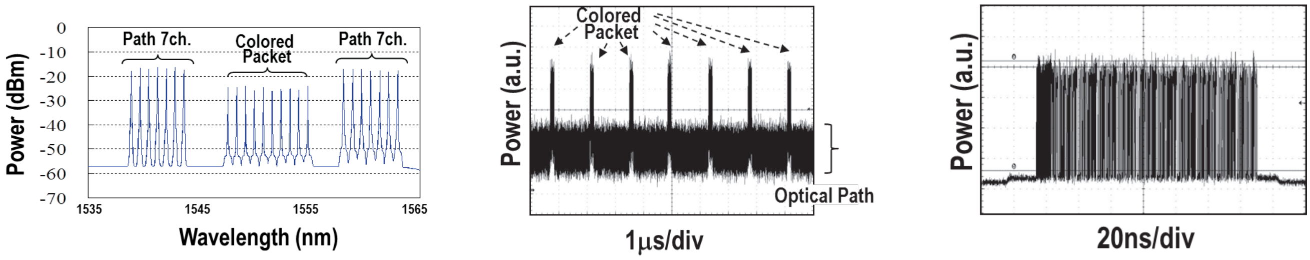
We verified moving boundary function of OPCInet, a function that dynamically moves the boundary between resources for optical packet services and those for lightpath services in order to meet change of user needs. Namely, all the wavelengths used in an optical fiber are shared among all application services and according to the moving boundary shown in Fig. 6, packet switching and circuit switched are used flexibly. We developed autonomic distributed control software that adjusts wavelength resources for optical packet switching and circuit switching according the number of in-use lightpaths. We have achieved 500 msec or fewer configurations, where the waveband for circuits is automatically increased or decreased according the increase or decrease in the number of lightpaths on the target link, on the previous experimental system[9]. This time is short enough because it is rare that rapid fluctuations of data traffic (optical packets and optical paths) occur within 500 msec. We have implemented this mechanism for the OPCI nodes[10]. We embedded autonomic distributed moving boundary mechanism in the OPCI nodes and verified reconfiguration of optical components for automatic moving boundary of each optical link, where boundary is moved according to the number of in-use lightpaths in each link[12].

4.2 Development OPCInet testbed and deployment to Internet access line

We succeeded error-free (frame-error-rate < 10^{-4}, regulated as a high quality in ITU-T Y.1541) 5-node hopping and 244 km single-mode fiber transmission of multiplexed 14-wavelength 10 Gbps optical paths and 100 Gbps optical packets in the OPCInet[8]. We then developed

Table 1 Packet error rate performance of optical packet and circuit integrated networks

Route (via OPS link)	Frame Error Rate (FL:64 Byte, PR:1%)	Frame Error Rate (FL:1518 Byte, PR:1%)	Frame Error Rate (FL;9000 Byte, PR:1%)	Frame Error Rate (FL;64 Byte, PR:10%)	Frame Error Rate (FL:1518 Byte, PR:10%)	Frame Error Rate (FL:9000 Byte, PR:10%)
Tester 1 → Node 1 → Node 2 → Tester 4	< 5.26E-10	< 3.84E-9	< 2.12E-8	< 2.50E-11	< 7.78E-10	< 2.00E-9
Tester 3 → Node 2 → Node 1 → Tester 2	< 5.26E-10	< 3.84E-9	< 2.22E-8	< 2.50E-11	< 7.87E-10	< 2.00E-9
Tester 2 → Node 1 → Node 2 → Node 1 → Tester 1	1.55E-6	4.53E-7	2.37E-5	2.50E-11	4.65E-9	4.00E-9
Tester 4 → Node 2 → Node 1 → Node 2 → Tester 3	1.67E-5	1.85E-6	7.58E-5	2.50E-11	7.82E-10	4.44E-6



Wavelength spectrum

Temporal waveform where optical packet signals and circuit signals are multiplexed

Temporal waveform of a single wavelength of an optical packet

Fig. 5 Waveform of optical packet signals and circuit signals

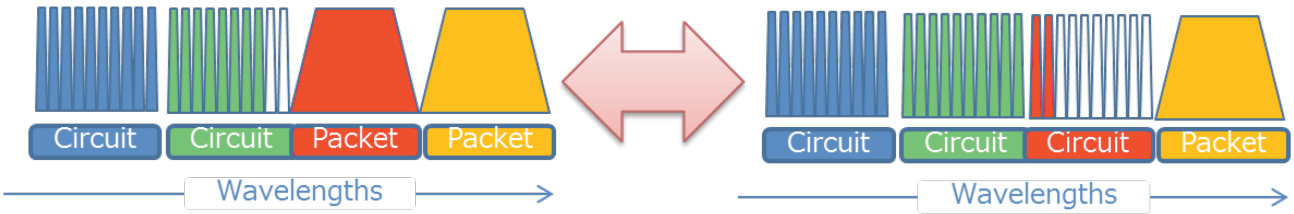


Fig. 6 Moving boundary between optical packet resources and optical circuit resources

OPCInet testbed by using optical dark fibers between NICT Headquarters (Koganei, Tokyo) and NICT Otemachi (near Tokyo Station) provided by JGN-X[13]. Figure 7 shows testbed network overview and monitored traffic. The network forms a multi-ring OPCInet and optical buffer is equipped. Since the length of the dark fiber is 44 km, the total length of 5-hop switching is 210 km.

Except for advanced experimentation of the optical systems, the OPCI nodes have been incorporated into the lab network to the Internet for stability verification and operation enhancement[4]. The OPCI nodes are used as the access network for the authors and other members in Lab if other specific experiments are not conducted. Figure 8 shows an example experimental network that is connected to the access line to the Internet. The OPCI nodes uses layer 3 switches that have a 100 Gbps optical packet interface[14], which will be described later. We also developed network management system having visualizing lightpath setup status, equipment fault, and the number of passed optical packets[15] via collaboration to the industry.

4.3 Increase in the capacity of network testbed

The above-mentioned client interface of OPCI node only has a single 10 Gbps Ethernet port[7]. We have thus tried to increase the capacity of the client network and developed a layer 3 switch having 100 Gbps optical packet interface and 12 10GbE interfaces[14]. Table 2 and Fig. 9 show specification and photograph of the developed layer 3 switch, respectively.

4.4 Software defined networking extension

We designed and implemented an SDN based interoperability framework between data centers and OPCInet, which is contributed to SDN extension to OPCInet. To set up a data path between two data centers, an SDN controller configures a set of flows to all of node equipment on the path. On the way of the path, if flow tables in OpenFlow switches (OFSes) are not configured appropriately, the necessity flows are configured at the OFS. Moreover, if no appropriate lightpath exists, the SDN controller requests a lightpath to the SDN controller. Thus, end-to-end data path is established by proper communication to the SDN controller and the control system of the OPCInet.

Figure 10 shows overview of the illustrated working experiment. We developed an OPCInet consisting of two data centers (OFSes and virtual machines (VMs) provided by JGN-X) and OPCI nodes. Data centers and OPCI nodes are connected by using optical dark fibers, VLAN-based L2 links also provided by JGN-X[16]. A Trema-based OpenFlow controller controls OFSs and OPCI nodes.

We described experimental results for interwork between OpenFlow control and lightpath establishment[16]. As we described, when an OpenFlow controller (OFC) configures a flow table of OpenFlow switches (OFSes) in the data center but no appropriate lightpath in the OPCInet, OFC requests the OPCInet a lightpath between

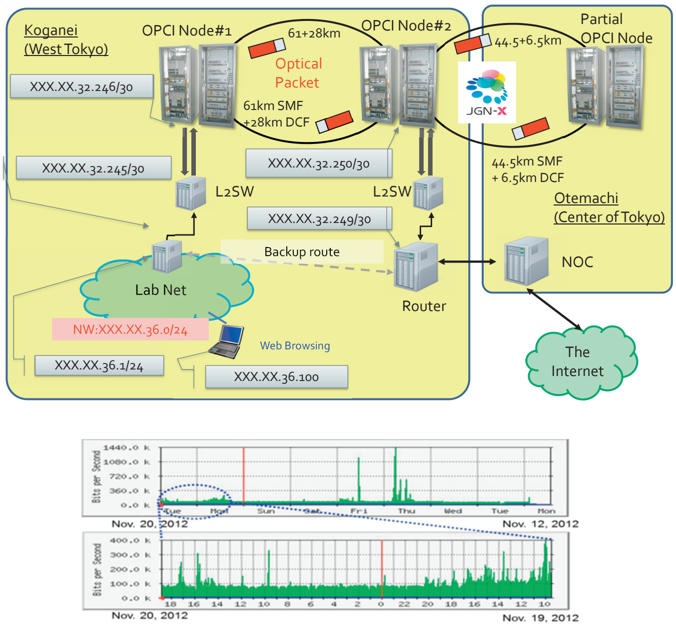


Fig. 7 OPCInet testbed by using laboratory network and JGN-X

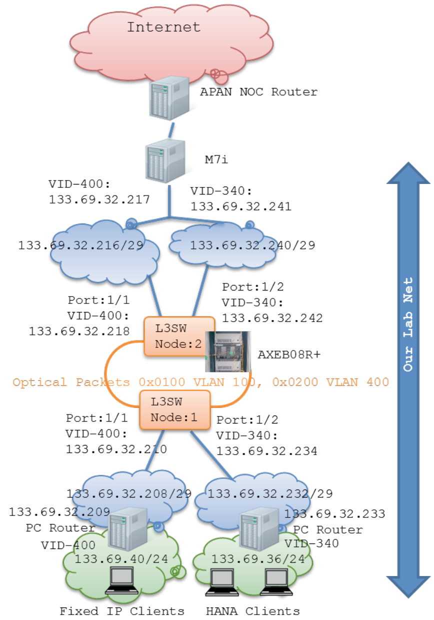


Fig. 8 Testbed enhancement by the use of optical packet switches having 12 10GbE interfaces

Table 2 Specifications of the layer 3 switch capable of 100 Gbps optical packet interface.

Items		Remarks
Port	10 GBASE-LR	12 ports
	100 Gbps optical packet	1 port
IP	IPv4, IPv6	Unicast forwarding
	Routing	Static only
	Table size	12,000 entries
	Lookup	Longest prefix matching
ARP (Ethernet I/F only)	ARP	Available
	ND	Solicitation, advertisement
	Table size	4,000 entries
	Aging	N/A
	Static ARP	Available
ICMP	ICMP/ICMPv6	Echo reply to echo request. N/A when an error occurs
VLAN	Capabilities	insert, delete, replace
# of client IPs	4 IPv4 addresses and 4 IPv6 addresses	for each port/VLAN
# of optical addresses	4,000 addresses	
Statistics	# packets, # bytes, # discarded packets	

the OFSes and the OPCInet configures it. This can combine our developed SDN environment for data center-OPCInet interworking. Figure 10 shows the round-trip time (RTT) measured by ICMP echo request/reply between two VMs that is corresponding to two end points of data. Initial condition was that no appropriate flow is set to OFS but a route in OPCInet is set appropriately. In each measurement result, the RTT of the first echo packet is around 30 msec and following echo packets are around 2 msec. We observe that the flow table is set appropriately when the first echo packet arrives at the OFS and the OFS forwards following echo packets by looking at the flow table.

In the above-mentioned experiment, mapping between destination IP addresses and lightpaths or optical packet address are pre-computed and reserved at SDN controller. Data path is configured by adding flow entry of the flow table in OPS and/or requesting a lightpath or routing of optical packet to OPCInet according to the reserved mapping information. To enhance generality and flexibility, we developed an SDN controller having path computation function. The controller maintains required bandwidth and remaining bandwidth between data centers, determines service quality by using the network load (i.e., link utilization) and finds the appropriate route for satisfying QoS for

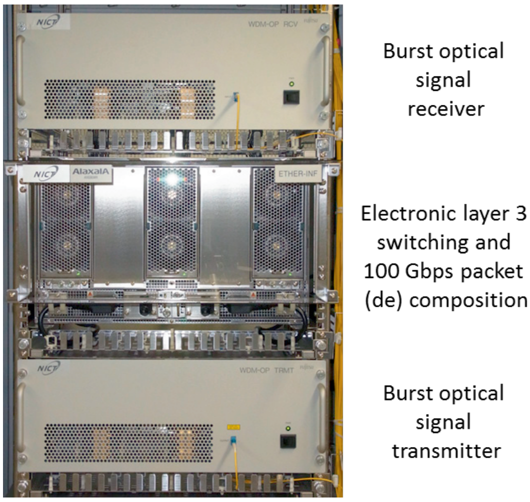


Fig. 9 A layer 3 switch capable of 100 Gbps optical packet interface and 12-port 10GbE

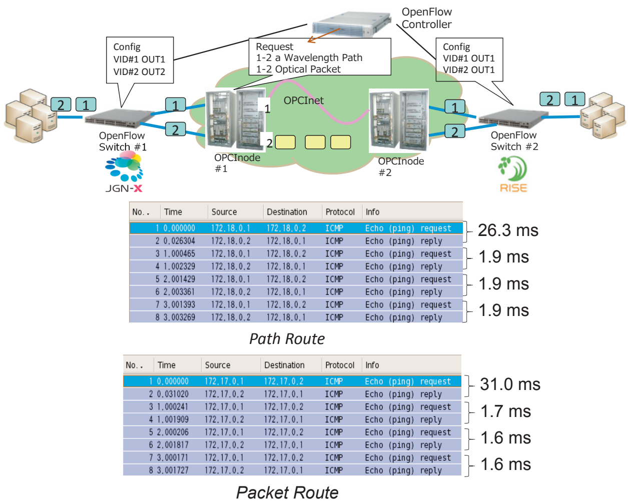


Fig. 10 A network consisting of RISE OpenFlow switches and OPCI nodes and reachability check result. Delay for the first packet is longer than others, because a flow is added to the flow table at that time.

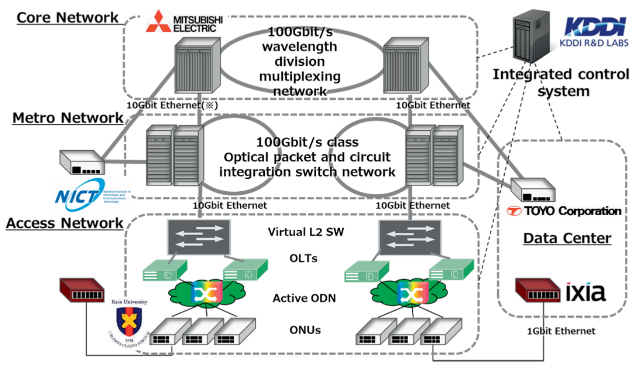


Fig. 11 An example optical transport network consisting of optical core, metro, and access networks and data centers integrated and managed by SDN (see NICT press[20]). It was demonstrated at iPOP 2014.

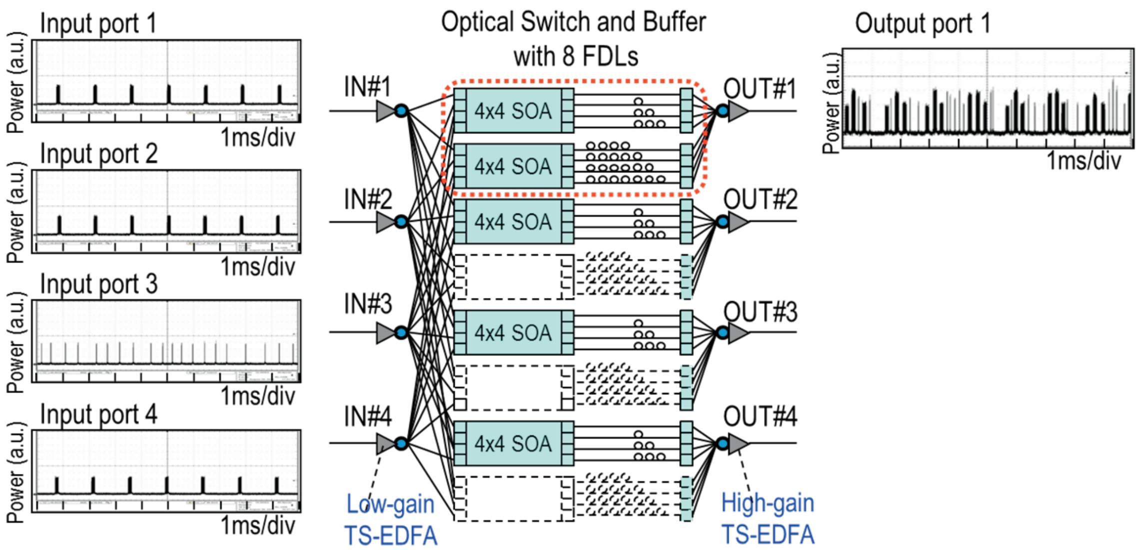
a service[17]. In this controller, if the quality is better than requested QoS, an existing lightpath or a packet route is used for the service, otherwise a new lightpath is setup.

Further, through collaboration with industry, we developed an SDN controller that is capable of configuring switching table of optical packet portion of the OPCI node[18]. Before that, we have already developed a user interface for configuring switching tables of OPSs and for layer 2 switches via Web interface[19]. The SDN controller is now able to set tables for OPCInet. Moreover, as we depicted, we have succeeded interoperability for optical SDN network. As shown in Fig. 11, we demonstrated inter-operable verification by collaboration with industry and academia. We demonstrated interoperability of SDN management where OpenFlow-based end-to-end optical path is configured for multi-domain/multi-technology optical transport networks. We proposed abstraction as an approach to different switching capabilities, and we verify experimentally OpenFlow-based dynamic path provisioning across optical access networks, 100 Gbit/s OPCI metro networks, and a 100 Gbit/s WDM core network[20][21]. This SDN technology is expected to be applied for realizing a wide-area cloud network that connects data centers and handles large volume of data.

4.5 Other enabling technologies such as optical buffer and address lookup

We conducted R&D on optical buffering and electronic header processing of optical packets for high-speed control technologies for OPCI nodes. Developing optical packet buffer is one of the most difficult hurdles when difficulty of storing optical signals is featured. We developed optical packet buffer consisting of SOA switch array and different length optical fibers and integrated it into OPCI nodes. The buffer provides up to 4[4] or 8[22] different delays and handles arriving packets first-come-first-service discipline. Figure 12 experimentally shows that the packet loss probability of 8 fiber-delay-line buffer is around 10^{-5} when arrival rate is 30%[22].

Increasing the number of stages of optical buffer leads to degradation of optical signal quality. Thus, we also conduct a study of optical and electronic combined buffer where electronic buffer is supplementarily used with optical packet buffer. We show that our proposed buffer architecture with scheduling algorithm reduces 30 % of power consumption in 1.7 time higher throughput conditions



8-FDL	IN#1 (Gbps)	IN#2 (Gbps)	IN#3 (Gbps)	IN#4 (Gbps)	Total IN#1 ~#4 (Gbps)	Packet Loss Rate
#1	4.59(500B)	5.74(1518B)	1.73 (64B)	--	12.06	0
#2	8.59(1518B)	8.69(1518B)	1.09 (64B)	8.66 (1518B)	27.03	7.6E-6
#3	8.59(1518B)	8.69(1518B)	8.54 (1518B)	8.66 (1518B)	34.48	1.2E-5

Fig. 12 Optical fiber-delay-line buffer using 8 different delay lengths. Buffer operation example and packet loss probability performance.

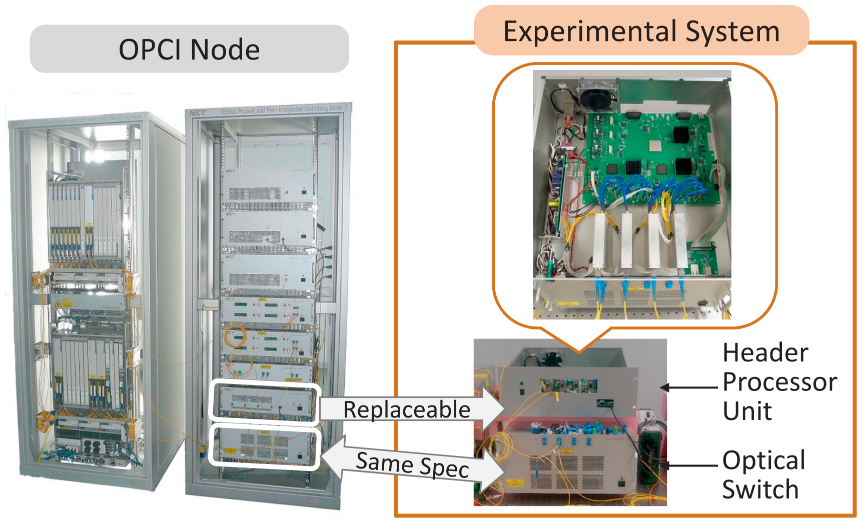
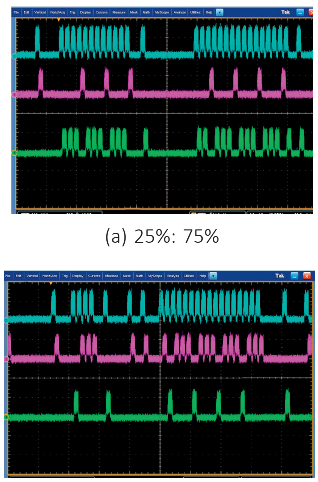


Fig. 13 Header processing unit for longest prefix matching address lookup and optical switch driven by the lookup result, which was been embedded in the OPCI node.



(a) 25%: 75%

(b) 75%:25%

Fig. 14 Switching result by 32-bit LPM result (upper: input, middle and bottom: outputs)

compared to electronic only buffer[23].

We have described that O/E conversion is decreased as much as possible for the purpose of utilizing optical broadband property. On the other hand, header processing of optical packets is handled electronically, we have to solve bottleneck of electronic processing speed and power consumption. We developed header processing unit where 100 Gbps optical packets are looked up by longest prefix matching policy and by using a new search engine LSI of which power consumption is 5% of traditional TCAM (Ternary Content Addressable Memory) and interface is the same as the TCAM[24][25]. We succeeded optical packet switching by the use of the header processing unit[26]. Figure 13 shows our developed header processing unit and optical switch used in our experiment. The latency between optical packet input and control signal output of optical switch is 506 ns. We now embed this header processing unit into OPCI node. The processing works with

161 MHz frequency and provides 32-bit LPM. Namely, if IPv4 address is copied into optical packet address, OPS can handle IP addresses used in the access networks. Figure 14 shows optical packet switching result where optical packets including 32-bit destination addresses are inputted (blue colors) and the optical packets are switched to different ports appropriately based on the longest prefix matching (red colors and green colors).

5 Concluding remarks

Toward deployment to the core of the NWGN for diversified services and high-speed and energy efficient infrastructure, our R&D has been devoted to optical packet and circuit integrated networks. We have addressed our outcomes such as development of 100 Gbps-class OPCI nodes, development of OPCInet testbed, operation in the Internet access line, and extension to SDN. We will practically use these OPCI nodes by installing them to network testbed.

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