Photonic Network Technologies for New Generation Network

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SUMMARY In this paper, we show the recent progress of photonic network technologies for the new generation network (NWGN). The NWGN is based on new design concepts that look beyond the next generation network (NGN) and the Internet. The NWGN will maintain the sustainability of our prosperous civilization and help resolve various social issues and problems by the use of information and communication technologies. In order to realize the NWGN, many novel technologies in the physical layer are required, in addition to technologies in the network control layer. Examples of cutting-edge physical layer technologies required to realize the NWGN include a terabit/sport or greater ultra-wideband optical packet switching system, a modulation-format-free optical packet switching (OPS) node, a hybrid optoelectronic packet switching node, a packet-based reconfigurable optical add/drop multiplexer (ROADM) system, an optical packet and circuit integrated node system, and optical buffering technologies.

key words: new generation network, optical packet switching, optical packet and circuit integrated network, transparent switching, burst-mode devices

1. Introduction

The remarkable advances in telecommunications technology in recent years have brought about a new information revolution that ranks alongside the industrial revolution. Today, the Internet is an essential part of our social infrastructure not only in the business world but also in our everyday lives. The Internet, however, is facing a crisis. The Internet was invented in the late 1960s, originally for use as a kind of communication tool for closed research communities and for communication links among computers. Today, around 1,000,000,000 hosts are connected to the Internet, and the number is still increasing. The Internet architecture has been extended in an attempt to accommodate boundless user demand, but the thin veneer of expansion of the Internet has come off, and it is now difficult for the Internet to respond to newly emerging social demands.

There is much activity in the design of post-Internet or future networks around the globe [1], [2]. The New-Generation Network (NWGN), a Japanese project which is one of these activities, is based on new design concepts looking beyond the next-generation network (NGN) and the Internet. In short, it aims to fundamentally solve the difficult issues and limits in an improved and extended Internet by taking a clean-slate design approach, unconstrained by existing technologies. Research and development of the NWGN is now being conducted as a Japanese national project. The NWGN will emerge in 2015 to 2020 [3].

As for the medium- to long-term research and development (R&D) strategy, the National Institute of Information and Communications Technology (NICT) published its NWGN vision, involving five network targets. The vision is derived from discussions about what and how NICT should contribute to create a prosperous society of the future. The five network targets represent functional network requirements. They are “Value Creation Network,” “Trustable Network,” “Ambient/Ubiquitous Network,” “Self-configuring Network (Connectable network without restrictions),” and “Sustainable Network.” It should be noted here that our technological strategy is not seeds-oriented but rather needs-oriented. General technological strategies and roadmaps have been established using an incremental approach that is an extension of today’s technology [4].

AKARI is an NWGN architecture project. AKARI has produced designs of several enabling components, such as optical packet and circuit integrated networking for diversity inclusion, network virtualization for sustainable networking, a regional wireless/sensor platform network for reality connection an identifier (ID)/locator split network architecture, and robust and self-organized networking [5].

In order to realize the NWGN, many novel technologies are required in the physical layer in addition to those in the network control layer. In this paper, some cutting-edge physical layer technologies for the NWGN are described, including a terabit/sport or greater ultra-wideband optical packet switching (OPS) system, a modulation-format-free OPS node, a hybrid optoelectronic packet switching node, a packet-based reconfigurable optical add/drop multiplexer (ROADM) system, an optical packet and circuit integrated node system, and optical buffering technologies.

2. Photonic Technologies for the NWGN Physical Layer

In the physical layer of the NWGN, high scalability, fine granularity, and flexibility will be very important, in addition to increased network capacity [5], [6]. In the NWGN, optical channels of varying granularity, such as path/burst/packet in the time domain and nar-
row/wide/bundle in the spectral domain, should be used as a pool of physical layer resources depending on the application (i.e., provider-by-provider, service-by-service, and so on) [5]. Here, we describe packet switching technologies in particular.

The basis of the physical layer of a photonic network is transmission technology in the links and switching technology in the nodes. The transmission capacity per fiber can be increased to over 60 Tbit/s by using various optical multiplexing methods and modulation formats, such as differential quadrature phase shift keying (DQPSK) and quadrature amplitude modulation (QAM) [7], [8]. In addition, orthogonal frequency division multiplexing (OFDM) technology [9] has the potential to enable flexible-bandwidth transmission.

On the other hand, the node-throughput is generally limited due to electronic processing in the node systems. In current electronic high-end IP routes, layer-1 and layer-2 switches, high-speed (i.e., wideband) optical signals are received and demultiplexed into low-speed (i.e., narrowband) electrical signals and parallel electronic processing is employed. However, many line cards and a large-scale electronic switch causes a serious power consumption problem. In addition, as the modulation formats of optical signals become more sophisticated, more complex receivers (e.g., high-speed digital signal processors or optical circuits controlling the phase with high accuracy) become necessary.

An OPS system, which can implement high-throughput forwarding of optical packets without optical-to-electrical-to-optical (O/E/O) converters in the physical layer, is quite attractive for node systems with energy-efficient processing and transparency for various bit rates and formats. Despite the limited functionality of optical technologies, various OPS systems have been developed for more than 15 years to exploit the potential abilities of OPS systems [10]–[22]. Although OPS systems themselves have not been used in commercial networks at present, they play an important role in the research activity as a vehicle leading to many novel basic technologies. These novel technologies are necessary to realize the physical layer of the NWGN, as well as OPS systems. There has also been significant evolution in the hardware systems for OPS nodes. Many important functions, which were difficult to achieve 10 years ago, have been developed and are now used in prototype-level demonstrations. These OPS technologies and various related technologies born from OPS research will serve as an important, novel technological basis for realizing the NWGN, and also for novel transmission technologies.

3. OPS Systems

3.1 DWDM-Based OPS System

OPS systems with optical label processing, optical switching, optical buffering, and electrical scheduling [14], [18], [19], [23]–[25] have been proposed and developed at NICT. In addition, we have introduced colored optical packets based on dense wavelength division multiplexing (DWDM) technology, which consists of multiple low-speed (10 Gbit/s or lower) payloads with different wavelengths, because this is more compatible with the mature signal transmission systems and interfaces of low-speed networks compared with those based on optical time division multiplexing (OTDM) [26]. By using a combination of DWDM technology and multilevel modulation formats, the data rate of optical packets can be drastically increased. In this section, we report on the transparency for various formats and the energy efficiency of our OPS system. We also present a recent demonstration of 1.28 Tbit/s (20 Gbit/s × 64 wavelengths) DWDM and DQPSK optical packet switching, as well as the network scalability of our OPS system [25].

OPS networks which provide wideband data transport are suitable for applications at the metro level and as part of the core network. As an example application, the architecture and the layered structure of IP over OPS networks are illustrated in Figs. 1(a) and 1(b), respectively [27]. In each edge node, the OPS network is connected with some IP-based metro or access networks. Some of these metro or access networks may consist of Ethernet technology (e.g., 10 Gigabit Ethernet). In order to provide high-throughput data transfer, the OPS network is deployed as a layer-2 network. While OPS networks can provide wideband transmission, for example, over 80 Gbit/s, other metro or access networks do not. As shown in Fig. 1(a), an IP packet and an optical packet are interchanged in a one-to-one mapping in the edge nodes. In addition, the destination information in the IP packet is associated with that in the optical packet via layer-3 (see Fig. 1(b)). Since these IP addresses can be flexibly assigned to various networks, it is possible to connect between different networks. Then, IP packets can be efficiently transferred through the OPS network.

Since ultra-short optical pulses are likely to be distorted due to dispersion or nonlinear effects in long-haul fiber transmission, it is difficult to develop OTDM-based high-speed optical packet transmission systems. To overcome the distortion problem in long-haul fiber transmission, we introduced large-capacity colored optical packets using DWDM technology [26]. As shown in Fig. 2, a DWDM-based optical packet consists of multiple 10 Gbit/s optical payloads of N different wavelengths and an optical label. The data rate
of the multiple optical payloads in the DWDM-based optical packet is $N \times 10\,\text{Gbit}/\text{s}$. Since 10Gbit/s optical transmission systems are mature and are easy to interface with electronic systems, we can develop an OPS system more easily compared with a system based on OTDM technologies. In addition, various modulation formats, such as on-off keying (OOK), differential phase shift keying (DPSK), DQPSK, and QAM, can be combined.

In order to realize an IP over DWDM-based OPS network, we developed novel network-interface devices (10 GbE/80 GbOP converters), each having one 10 Gigabit Ethernet (10 GbE) interface and one 80 Gbit/s optical packet (80 GbOP) interface [27]. If the converters have eight 10 GbE ports, we can use the full bandwidth of 80 Gbit/s OPS networks even at the edge nodes. Figure 3 shows the configuration of a 10 GbE/80 GbOP converter. An IP packet in a 10 GbE frame is converted from the optical domain to the electrical domain and is segmented into eight electrical payloads, each of which is about 10 Gbit/s. Then, the eight electrical payloads are output to different ports at the same timing. Eight E/O transmitters operating at different wavelengths are arrayed and generate eight wavelength-channel 10 Gbit/s optical payloads. In parallel, an IP header processor refers to a look-up table and outputs electrical label signals, which are converted into optical labels by optical encoders. Finally, an 80 (8$\times$10) Gbit/s DWDM-based optical packet with an optical label is output by multiplexing with an arrayed waveguide grating (AWG). To convert the 80 (8$\times$10) Gbit/s DWDM-based optical packets into 10 GbE frames, the reverse operation is implemented.

3.2 Transparency and Energy Efficiency of OPS System

Our OPS system consists of optical switches and optical buffers in the data plane, and optical label processors and an electrical scheduler in the control plane, as shown in Fig. 4. The label processing is passively performed using an optical correlation technique [28]. Each optical buffer consists of optical switches and optical fiber-delay-lines (FDLs) which give a fixed delay. Recently, it has been reported that the scheduler is compatible with asynchronous variable-length optical packets [29].

We have developed an OPS prototype and showed the possibility of transparent operation for various formats and bit rates through demonstrations such as 160 Gbit/s OTDM/OOK [23], 640 Gbit/s DWDM/OOK [24], 640 Gbit/s DWDM/DPSK [30], and 1.28 Tbit/s DWDM/DQPSK [25] optical packet switching, as shown in Fig. 5(a). We also examined the energy efficiency ratio (EER) of our OPS prototype, as shown in Fig. 5(b). The EER is defined as the total number of processable bits per joule [31]. The data rate can be increased without a large increase in power consumption because devices of the same type are used in each demonstration. The power consumption of these prototypes during operation was about 1.0 kW. As a result, the growth rate of the EER of the OPS prototype was higher compared with that of high-end electronic routers [24]. Therefore, OPS systems are expected
the buffered packets in buffers 1-1 and 1-2, respectively. The dotted ovals show packet avoidance. Figure 6(g) shows merged optical packets at output port 1. Figure 6(h) shows the bit error rates (BERs) of the demodulated I and Q data in the 64 channels. Error free (BER < 10^-9) operation and a power penalty of less than 6 dB were achieved for all channels.

There is a scalability issue of the number of nodes because optical packets are transmitted through several OPS nodes connected in series in practical OPS networks. In [32], we investigated the number of nodes through which optical packets can hop when a 640 Gbit/s/port DWDM/OOK OPS prototype is assumed as a node. Figure 7 shows the simulation results. The key component is the optical switch, and the number of nodes can be scaled up to eight, especially if the insertion loss and the crosstalk of the optical switches are improved.

4. Hybrid Optoelectronic Packet Switching Node

Here, we introduce a hybrid optoelectronic packet switch, enabling both highly functional electronic processing and wideband optical processing, developed by NTT Photonics Laboratories [33], [34]. The switch consists of label processors, an optical switch, and an electrical shared buffer, as shown in Fig. 8(a). The optical processing technology has little flexibility compared with electronic processing though it is important for achieving wideband performance and energy-saving. Moreover, an optical memory has not been achieved yet. Therefore, in the hybrid optoelectronic switch, electronic processing has been introduced into the label processing part and the shared buffer, which need logical operations.

The label processing is mainly achieved with an optically clocked transistor array (OCTA), which performs serial/parallel conversion (SPC/PSC) and O/E/O conversion between optical labels and electrical signals, and complementary metal oxide semiconductor (CMOS) circuits. The output port of an optical packet is decided by a CMOS circuit, referring to an optical label and a routing table. Moreover, a new optical label can be added to an optical packet. The optical switch is based on an AWG converter (TWC), which mainly consists of a burst-mode re-
receiver, a LiNbO$_3$ modulator, and a double-ring-resonator-coupled tunable laser diode. Optical packets without packet-collision are sent to an appropriate output port with low latency by the wavelength routing, and optical packets with the possibility of the collision are forwarded to the shared buffer. In the shared buffer, serial-parallel conversion and O/E conversion for optical packets are implemented, and electrical signals are stored in CMOS-RAM. In this case, QoS (Quality of Service) control, multicasting, and waveform regeneration can be achieved by making the best use of the functionality of electronic processing.

The developed prototype has an 8 × 8 switch, and processing for asynchronously-arriving variable-length optical packets is executed at 10 Gbit/s in each port [34]. Figure 8(b) shows a photograph of the prototype. The delay time of the entire system is 380 ns in the case of no collision, and 1.4 μs including the collision avoidance operation. The total throughput is 160 Gbit/s, and the power consumption is 360 W. For reference, we provide information that the power consumption of an electronic router with 120 Gbit/s throughput is 2.2 kW [35]. Note that we can not simply compare their power consumption between the electronic router and the developed prototype because available functions of their systems are different.

5. Packet ROADM System

Recently, one application of optical packet switching technologies, a packet-based reconfigurable optical add/drop multiplexer (P-ROADM) system for optical packet ring networks, has been proposed, as shown in Fig. 9 [36]-[39]. Compared with conventional ROADM ring networks based on wavelength paths, the P-ROADM network provides fine granularity. In addition, the ring topology reduces the burden on optical buffers because the possibility of packet collisions is decreased.

A P-ROADM based on high-speed optical-code label processing has been proposed and developed at NICT [36]. Recently, a field trial of a flexible-granularity, 3-node, 16-wavelength WDM optical network at 40 Gbit/s over 173 km was demonstrated with a 640-Gbit/s throughput P-ROADM prototype with label-selectivity-enhanced optical en/decoders and a wide-passband acoustooptic wavelength-tunable filter (AOTF) for 40-Gbit/s signals [37].

Alcatel-Lucent Bell Labs has also proposed an optical packet ring network based on P-OADM technology and developed a demonstrator [38]. In the proposed network, the data packets and the control packets, including the headers used to route the packets, are separately transmitted. Recently, a new metro network architecture that transparently interconnects P-OADM ring networks through an NTT hybrid optoelectronic packet switch [34] has been demonstrated [39]. The combined system operated error free in unicast and multicast transmissions at 10 Gbit/s, and traffic management was verified using an out-of-band control protocol and synchronization for the insertion of packets.

6. Optical Packet and Circuit Integrated Node System

In the NWGN [5], energy efficiency and high throughput are essential. It is also necessary to provide diversified services, such as best-effort and quality of service (QoS) guaranteed services. To satisfy these demands, we have proposed an optical packet and circuit integrated network, as shown in Fig. 10(a) [5]. The integrated network provides both OPS links, which enable bandwidth-sharing and best-effort data transferring, and optical circuit switching (OCS) links, which enable a fully occupied bandwidth and end-to-end QoS-guaranteed data transmission, based on common wavelength resources and fibers [40], [41]. By dynamically sharing wavelength resources between the OPS or OCS links [42], new or urgent services can be supported. By multiplexing control packets for signalling and resource control on the OPS links, the need for additional interfaces is reduced and the network is simplified.

In the proposed integrated network, wavelength resources are divided into occupied wavebands of the OPS and OCS links and shared wavebands. The shared wavebands are allocated to the OPS or OCS links depending on the demands for lightpath establishment or packet transfer-
7. Conclusion

We have shown the recent progress of photonic network technologies for the new generation network (NWGN). The NWGN is based on new design concepts that look beyond the next generation network (NGN) and the Internet. In order to realize the NWGN, many novel technologies are required in the physical layer in addition to those in the network control layer. In the NWGN, optical channels with varying granularity, such as path/burst/packet in the time domain and narrow/wide/bundle in the spectral domain, should be used as a pool of physical layer resources depending on the case.

Cutting-edge physical layer technologies for the NWGN have been described, such as a terabit/s/port or greater ultra-wideband optical packet switching (OPS) system, a modulation-format-free OPS node, a hybrid optoelectronic packet switching node, an optical packet ROADM system, an optical packet and circuit integrated node system, and optical buffering technologies. In addition, we list other related key technologies such as a polarization-independent optical switch [43], burst-mode Tx. and Rx. [27], and a burst-mode erbium-doped fiber amplifier (EDFA) [44] as references. These OPS technologies and various related technologies born from OPS research will serve as an important, novel technological basis for realizing the physical layer for the NWGN, and also for novel transmission technologies.

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References


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