A circuit may transit more switching nodes or require more which has a smaller capacity than that of transmission path. Quality, and cost-effective broadband communication networks for high-speed, high-quality, and cost-effective communication services. A path is a bundle of circuits. It has a large capacity and is generally more cost-effective per bit than a circuit, which has a smaller capacity than that of transmission path. A circuit may transit more switching nodes or require more processing cost than a path in order to adopt dynamic traffic demand changes in a timely manner. A path is configured based on the traffic demand prediction. A circuit is setup based on each user request. The holding time of path is usually longer than that of circuit. A circuit has more flexibility than a path according to the traffic demand changes. The traffic utilization of path tends to be less than that of circuit. Thus, there is a tradeoff between transmission capacity and network utilization. Network operators should appropriately bundle small-capacity circuits into a large-capacity path, considering the traffic demands, which can be dynamically changed, and the transmission and switching technologies to be deployed.

Optical networks have been evolved with networking technologies and device and system technologies. Networking technologies include design and control of paths, traffic engineering, network operations, network protocols, addressing, applications, and integrations of hardware and software. Device and system technologies include the optical transmission systems, optical cross-connects, optical switches, and their devices.

This paper reviews past and recent trends of optical networks and addresses the future directions. First, we describe path networks with the historical backgrounds and trends. Path networks have advanced by using various multiplexing technologies. They include time-division multiplexing (TDM), asynchronous transfer mode (ATM), and wavelength-division multiplexing (WDM). ATM was later succeeded to multi-protocol label switching (MPLS). Second, we present generalized MPLS technologies (GMPLS). In GMPLS, the label concept of MPLS is extended to other labels used in TDM, WDM, and fiber networks. GMPLS enables network operators to serve networks deployed by different technologies with a common protocol suite of GMPLS. Third, we describe multi-layer traffic engineering and a path computation element (PCE). Multi-layer traffic engineering designs and controls networks considering resource usages of more than one layer. This leads to use network resources more efficiently than the single-layer traffic engineering adopted independently for each layer. PCE is defined as a network element that computes paths, which are used for traffic engineering. Then, we address software-defined networks, which put the designed network functions into the programmable data plane by way of the management plane. We describe the evaluation from GMPLS to software defined networking (SDN) and transport SDN. Fifth, we describe the advanced devices and switches for optical networks. Finally, we address advances in networking technologies and future directions on optical networking.

**key words:** optical networks, path, traffic engineering, path computation, optical devices, optical switches, software defined networking

**1. Introduction**

Traffic demands continue to increase explosively, and broadband communication networks become indispensable infrastructures. Optical networks are required to support the broadband communication networks for high-speed, high-quality, and cost-effective communication services.

A path is a bundle of circuits. It has a large capacity and is generally more cost-effective per bit than a circuit, which has a smaller capacity than that of transmission path. A circuit may transit more switching nodes or require more

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**INVITED SURVEY PAPER** Special Issue on the Past, Present, and Future of Communications Technologies in the IEICE

**Optical Networking Paradigm: Past, Recent Trends and Future Directions**

Eiji OKI†, Fellow, Naoya WADA††, Member, Satoru OKAMOTO†††, Naoaki YAMANAKA††††, and Ken-ichi SATO†††††, Fellows

SUMMARY This paper presents past and recent trends of optical networks and addresses the future directions. First, we describe path networks with the historical backgrounds and trends. Path networks have advanced by using various multiplexing technologies. They include time-division multiplexing (TDM), asynchronous transfer mode (ATM), and wavelength-division multiplexing (WDM). ATM was later succeeded to multi-protocol label switching (MPLS). Second, we present generalized MPLS technologies (GMPLS). In GMPLS, the label concept of MPLS is extended to other labels used in TDM, WDM, and fiber networks. GMPLS enables network operators to serve networks deployed by different technologies with a common protocol suite of GMPLS. Third, we describe multi-layer traffic engineering and a path computation element (PCE). Multi-layer traffic engineering designs and controls networks considering resource usages of more than one layer. This leads to use network resources more efficiently than the single-layer traffic engineering adopted independently for each layer. PCE is defined as a network element that computes paths, which are used for traffic engineering. Then, we address software-defined networks, which put the designed network functions into the programmable data plane by way of the management plane. We describe the evaluation from GMPLS to software defined networking (SDN) and transport SDN. Fifth, we describe the advanced devices and switches for optical networks. Finally, we address advances in networking technologies and future directions on optical networking.

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†The author was with The University of Electro-Communications, Chofu-shi, 182-8585 Japan.
††The author is with National Institute of Information and Communications Technology, Koganei-shi, 184-8795 Japan.
†††The authors are with Keio University, Yokohama-shi, 223-8522 Japan.
††††The author was with The University of Electro-Communications, Chofu-shi, 184-8795 Japan.
†††††The author is with Nagoya University, Nagoya-shi, 464-8603 Japan.
‡Presently, with Kyoto University, Kyoto 606-8501, Japan.
a) E-mail: oki@i.kyoto-u.ac.jp

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Finally, Sect. 8 concludes this paper.

Section 7 presents the development of optical networks. Section 6 describes devices and switches for optical engineering and PCE. Section 5 addresses software-defined networking (SDN) and transport PCE. Section 4 presents multi-layer traffic engineering technologies, including recovery from transmission line failures, and node failure and traffic engineering, are deployed on the transport network. A circuit is replaced by a virtual circuit. Multiple virtual circuits are accommodated into a virtual path (VP). A VP network works as a networking layer. A cell multiplexing technology is used in the VP and also the virtual circuit. Therefore, a capacity of VP is flexibly assigned with granularity 1 Mbps. On the other hand, SDH can assign stair-casing path capacities. To accommodate VPs into a transmission line, the whole capacity of SDH STMs can be used, such as VC-4 in STM-1, VC-4-4c (four contiguously concatenated VC-4s) in STM-4, and VC-4-16c (16 contiguously concatenated VC-4s) in STM-16. This means that adjacent ATM equipments can be directly connected without any SDH XCs and multiplexers, and networking is performed in an ATM VP layer. This trend of skipping SDH equipments was inherited to an Internet Protocol (IP) world. A Packet over SDH (POS) interface was equipped into IP routers. VC-4-4c was used in 600 Mbps POS interfaces, VC-4-16c was used in 2.5 Gbps POS interfaces, and VC-4-64c was used in 10 Gbps POS interfaces. Unlike the ATM network, the POS-based IP network did not have any networking layer in the transport network. Concatenated VC-4 containers are generated from...
TDM (or round-robin) based multiple streams with VC-4 rate. In the TDM manner, a time slot is cyclically assigned to each multiplexed signal. At a transmission side, a TDM multiplexer assigns a sending timing to each slot. Therefore, all slots are serialized into single stream data. At the receiver side, a TDM demultiplexer separates multiplexed data into each data stream by reading data with slot timing. In TDM, to improve the transmission line capacity, a slot time should be shortened. For example, to realize 10 times larger capacities, the bit time width of data should be reduced to 1/10. Therefore, it was difficult to enhance transmission capacity by the TDM technology only.

To break the limitation of TDM, the WDM technology was applied to the transmission system. In WDM, transmission capacity can be multiplied by the number of multiplexed wavelengths. To respond to enhance IP traffic growth, direct optical fiber connections between multiple IP router interfaces and WDM equipments were introduced, and WDM interfaces into IP routers were widely implemented. This is called as “IP over WDM” [4]. In the IP over WDM, IP router was directly connected into the transmission line. Therefore, it was difficult to realize changing a peer IP router and rerouting in case of failures. This is the same situation as the POS based IP network. Lack of the transport access path becomes a common problem in broadband services using concatenated VC-4 containers.

To solve this problem, an optical path concept was proposed [5, 6]. In an optical path network, each wavelength of WDM channel is defined as an optical path and an optical XC (OXC) is introduced to accommodate optical paths into WDM transmission lines. In OXC, destination (i.e., output optical fiber) of each wavelength is set in advance by configuring the optical path routing table. Therefore, without optical to electrical (O/E) conversion, the input optical signal is forwarded to output fiber port. An optical path can be defined as follows: a communication channel, which is established by configuring the routing table of one or multiple OXCs along with the route.

Two optical path categories have been proposed [5, 6]. One is a wavelength path (WP), which assigns the same wavelength along with the optical path route. Another is a virtual wavelength path (VWP), which can assign a distinct wavelength for each WDM transmission section, which is a section between two neighbor OXCs connected by optical fiber(s). Figures 3 (a) and (b) show a WP based optical path network and a VWP based optical path network, respectively. To set up an optical path, an optical path route and a wavelength of the optical path should be assigned. This is called the routing and wavelength assignment (RWA) problem [7, 8]. To solve the RWA problem, several heuristic algorithms were discussed [9–11]. In WP networks, the complex RWA should be solved since it requires wavelength continuity restriction, while it relaxes the complexity of OXC node structure [6, 7, 12] as it requires small size all optical switching systems. In VWP networks, wavelength conversion is allowed to reduce the computational complexity of the RWA problem, while it requires a large scale or large number of optical switches and all optical wavelength conversion modules [6, 7, 12]. Therefore, development of the VWP OXC was started by using an optical to electrical to optical (O/E/O) type wavelength conversion module [12–15].

Initially, the target of the optical path network was for providing the transport access path function to the service which did not have the path layer, such as an IP backbone network. As a next step, a grouped optical path has been proposed in [16, 17]. The grouped optical path was defined as bundled multiple optical paths and provided a hierarchical optical path. An optical path provides a service access path function and a grouped optical path provides a transport access path function. The development of the grouped optical path is still active [18, 19].

In 2010’s, a new service access path technology based on the optical transport network (OTN) [20], which is based on TDM technologies, is widely used in transport networks. The optical data unit (ODU), which provides 1.25 Gbps (ODU0), 2.5 Gbps (ODU1), 10 Gbps (ODU2), 40 Gbps (ODU3), and 100 Gbps (ODU4) paths, are defined, and ODU-XC is developed. Regarding with the OXC deployment, a reconfigurable optical add/drop multiplexer (ROADM) and multi-degree ROADMs, which can be used as OXC, are also used in the current transport networks.

3. Generalized Multi-Protocol Label Switching

MPLS [21] is an extension of IP. MPLS is a connection-oriented protocol, while IP is a connection-less protocol. The concept of MPLS is based on ATM, both of which are connection-oriented while packet/cell-based multiplexing is performed. In the MPLS network, a 20-bit shim header is attached to the IP packet. The shim label swapping technique is used to forward packets along with the path. MPLS has an advantages of high-speed switching, explicit routing, and guaranteeing the capacity as well as sophisticated traffic engineering. On the other hand, optical paths that have a huge capacity, simple protocols and low energy consumption in optical networks have an advantage of data transfer as described Sect. 2. However, it requires a larger capacity granularity.

Fig. 3 Optical path network.
To utilize the advantages of both technologies, which are MPLS and huge capacity optical paths, a general concept of the GMPLS protocol has been introduced, as shown in Fig. 4 [22], [23]. GMPLS has typically four types of labels, packet, TDM, λ and fiber; each type is called switching capability. Packet switching capability (PSC) uses an IP packet label, such as an MPLS label. A time slot position is used for a TDM label. Lambda switching capability (LSC) uses a wavelength, λ, as a label. Finally, fiber switching capability (FSC) uses a physical fiber port number as a label.

In the conventional network control, only the packet layer is controlled distributedly using routing protocols [24], [25] or signaling protocols [26]. In other layers, which are the TDM layer, the λ (optical-path) layer and the physical (fiber) layer, the network is centrally controlled by setting up routes or paths. In this environment, network operators need to learn how to operate each network corresponding to the respective layer, since different network control methods are used in the different layers.

By using GMPLS, it becomes possible to control all the layers distributedly by expanding MPLS to the TDM layer and the λ layer, as shown in Fig. 5. In this environment, the functions that were executed by a central controller are now allocated to each node and each layer in the network is controlled distributedly; the central controller to control the network per layer is not required. Thus, it becomes possible to flexibly address addition or deletion of nodes or links, resulting in improving scalability against the change of the network configurations. Moreover, as each layer is operated based on the same GMPLS protocol suite, human resources can be used more effectively; after learning and mastering the GMPLS protocol suites, the network operator is able to operate all of the layers in the same manner.

Furthermore, in the GMPLS network, it is possible to control the network distributedly by integrating multiple layers, as shown in Fig. 6; the network control functions are allocated to each node distributedly and the central controller to control the network across different layers is not required. The integrated traffic engineering for multiple layers is called multi-layer traffic engineering [27], [28]. Figure 7 shows the concept of this multi-layer traffic engineering. In this example, the network is composed of the packet layer, the λ layer, and the fiber layer. The topology of the λ layer changes corresponding to the change in traffic demands in the packet layer, and the route that a packet path selects is converted according to the change of topology in the λ layer. Since multiple layers can collaboratively adapt the topology or route of each layer to accommodate changes in traffic demand, multi-layer traffic engineering increases the efficient use of network resources.

Standardizing a suite of GMPLS protocols has been performed under the purview of the Internet engineering task force (IETF), which is a standardization organization on Internet-related matters. The major protocols used in GMPLS, is mainly composed of the open shortest path first (OSPF) extension of the routing protocol [29], the resource reservation protocol–traffic engineering (RSVP-TE) extension of the signaling protocol [30], and the link management protocol (LMP) [31].

Another key discussion on GMPLS is a multi-area, multi-autonomous system (AS), multi-carrier, and inter-working [32]. Between ASes, external network to network
A backbone network consists of multiple layers, which include physical, optical, and IP/MPLS layers, as shown in Fig. 9. An MPLS path, which we refer to as a packet path, is accommodated in optical paths, and an optical path is accommodated in optical fibers. The capacity of each optical path, which is 10-100 Gbps, can be much larger than that of each packet path. Since the capacity of packet paths is flexible, the IP/MPLS layer is well engineered. An ingress IP router establishes packet paths destined to each egress router. If the traffic demand between ingress and egress routers is enough large to utilize an optical path capacity, it is advantageous to establish directly an optical path between the two IP routers, and a packet path is accommodated in the optical path. Otherwise, the optical path is not fully utilized. It may be more efficient if the packet path is routed on multiple optical paths by way of some transit IP routers so that the traffic can be groomed with other traffic between other ingress and egress pairs. This agglomeration is called traffic grooming [35]. There are two main options for routing a packet path over the optical-path layer, which are single hop routes or multiple hop routes. A network provider determines an appropriate set of optical paths between IP routers to maximize the network utilization, considering the network resource conditions, including the number of available wavelengths and the number of available ports in IP routers.

The traffic grooming problems in a multi-layer network have been addressed in the literature [27], [28], [35]–[40]. The traffic-grooming problems presented in [35]–[37], [39] consider two layers of the SDH/synchronous optical network (SONET) and WDM layers. The essential traffic-grooming problem for optical-path layers and IP/MPLS layers is the same that for SDH/SONET layers and optical-path layers. References [35], [36] addressed traffic-grooming approaches in an off-line manner, where traffic demands are given in advance and the optimization problem is formulated and solved. Reference [27] developed a heuristic virtual network topology (VNT) design scheme based on traffic measurement for traffic demands to minimize the network cost in traffic-demand fluctuation.

The work in [37] addressed two grooming path computation approaches, which are two-layered path computation (TLPC) and single-layered route computation (SLPC) in a one-line manner. In the one-line approach, connections with different capacities are requested randomly. TLPC performs path computation separately over the two layers, while SLPC generates a new graph by integrating the two layers. TLPC is more beneficial than SLPC in terms of computation complexity. On the other hand, SLPC provides more efficient routes to utilize the network resources than TLPC. Reference [39] developed a generic integrated graph model in the SLRC approach by using different grooming policies. Under the TLPC approach, reference [28] addressed multi-layer two routing policies, which are existing optical path first and creating optical path first, for optical IP networks. It clarified the applicability for both policies depending on the number of available ports in IP routers and the number of wavelengths.

Reference [38] presented a distributed control mechanism to reconfigure VNT, where traffic demands are unpredictable and can be dynamically changed. A heuristic algorithm was developed to compute a suitable VNT to mitigate network congestion by establishing and tearing down optical paths, where several extensions of GMPLS-based protocols were introduced.

Traffic demands are difficult to predict exactly, but the network ingress and egress capacity constraints can be assumed. In this scenario with unpredictable traffic demands,
reference [40] addressed an IP routing strategy with provisioning optical networks. The presented strategy achieves load balancing in two stages across transit IP routers. An optimization problem was formulated as a linear programming problem to maximize the network throughput.

Reference [41] classified constraints for multi-layer path computation. The authors classified the constraints into prunable and non-prunable classes. The prunable class includes metrics by which the corresponding link can be filtered, or deleted to determine the path. The non-prunable class has more complex network element attributes, which includes switching capability and wavelength continuity. Reference [42] addressed traffic matrix models for multi-layer traffic engineering. They investigated several typical traffic models, and introduced a traffic matrix, which combines a spatio-temporal distribution with a 24 hour periodic variation.

4.2 Path Computation Element

Constrained-based path computation is a basic building block in MPLS/GMPLS networks. In the conventional network architecture, the path computation is considered as a part of the node function. A node includes a router and an OXC. The path computation function becomes more complicated for multi-layer and multi-domain traffic engineering, compared to single-layer and single-domain traffic engineering. In addition, network providers would like to have their own path computation function, since they want to use their computation algorithms based on their network operation policies. From the vendors’ points of view, it is not preferable to implement the path computation function that handles all the requirements by network providers. Therefore, it is necessary to separate the path computation function, which is called a path computation element (PCE), from the node function [43]. In [44], [45], a protocol for communication between a PCE and a node was introduced. The introduced protocol is called a generalized traffic engineering protocol (GTEP), as it was designed to perform path computation generally in any single-layer and multi-layer networks. They implemented GTEP in a PCE and a GMPLS router, and conducted a multi-layer traffic engineering experiment with GTEP.

These requirements and some protocol design and experimental efforts for PCE motivated the community of network providers and vendors to specify a PCE architecture and standardize communication protocols on PCE. Reference [46] described the PCE architecture, which defined all the functional components related to PCE and the set of building blocks. Reference [47] specified the PCE communication protocol (PCEP) between a PCE and a path computation client (PCC) based on the PCE architecture [46] and PCEP requirements [48]. PCC can be a node, PCE, and a network management system (NMS).

Reference [49] addressed a PCE-based framework for multi-layer traffic engineering, and introduced several network models incorporating PCEs. The framework includes the relationship between PCEs and VNT. In multi-layer path computation, the two models of path computation, which are a single PCE multi-layer path computation model and a multiple PCE multi-layer path computation model, were provided. In the single PCE multi-layer path computation model, a PCE has topology visibility into all layers. In the multiple PCE multi-layer path computation model, at least one PCE is associated with each layer, and has topology visibility into the layer. Multi-layer path computation to establish an end-to-end path across multiple layers is performed in cooperation with multiple layer-associated PCEs. Reference [50] discussed dynamic resource control based PCE in multi-layer networks from both vendors’ and network providers’ points of view.

When multiple path-computation requests or re-optimization requests for a set of path routes exist, it is beneficial to perform bulk path computation for multiple paths at the same time to utilize network resources more effectively rather than perform one path computation for each path. This bulk optimization on path computation is called global concurrent optimization (GCO). Reference [51] addressed application-specific requirements for PCEP and specified protocol extensions from [47] to support GCO. GCO simultaneously considers multiple path request and existing paths in the network and provides an optimal solution to satisfy the constraints for all the paths. GCO is mainly applied to path computation in an NMS.

To provide reliable communication services, disjoint path computation is required. Disjoint paths do not have any common link or any common node between a source and a destination. The former and the latter are called link-disjoint and node-disjoint paths, respectively. Link disjointness is a subset of node disjointness. In a multi-layer environment, working and backup paths are logically disjoint in the higher-layer network, but they are not always physically disjoint in the lower-layer network. The two logical links in the higher network may use a common physical link resource such a fiber in the lower layer. In this case, the two links belong to the same shared risk link group (SRLG). Path computation considering the SRLG constraints was presented in [52]. This SRLG-aware path computation scheme was implemented in a multi-switching-capable node, called a photonic MPLS router, which integrates IP/MPLS router functions and optical-path switching functions; a restoration was demonstrated by computing backup paths with the SRLG-aware path computation scheme [53]. Reference [54] addressed constraints for path computation to explicitly exclude SRLGs, abstract nodes, and resource from the computed route and specified PCEP protocol extensions. The extensions can be applied to multi-carrier path computation accessing different carriers, each of which keeps confidentiality of its network resources. An interoperability test on inter-carrier PCE-based path computation was reported in [55].
5. Software-Defined Networks

5.1 Evolution from GMPLS to SDN

In the GMPLS network, three planes distinctly separated architecture, which is widely used in transport networks, has been adopted. Three planes are a management plane (M-Plane), a data plane (D-Plane), and the control plane (C-Plane). By the GMPLS technology, C-Plane got a feature of programmability. D-Plane of IP and MPLS routers was processed by application specific integrated circuits (ASICs); realizing wire-rate packet processing was the first priority. In 2010’s, interfaces of routers are unified into Ethernet and near wire-rate packet processing becomes possible by the central processing unit (CPU) and software program on x86 based commodity platform. Other programmable high speed packet processing devices, such as a network processor (NP), a field programmable gate array (FPGA), general-purpose computing on graphics processing unit (GP-GPU), and reconfigurable processor (RP) becomes also popular. This trend introduces programmability into D-Plane.

SDN can be defined as follows: putting the designed network functions into the programmable D-Plane via M-Plane. Behaviors of the programmable D-Plane are defined by the software. In addition, in the SDN world, several application programming interfaces (APIs) become open to users. This leads accessibility from user applications to M-Plane. Current legacy M-Plane exists between an operator (human) and a network (machine). A graphical user interface (GUI) is used to reflect operators’ will to the network; it realizes human-to-machine (H2M) communications. A software program in C-Plane is run based on instruction from the M-Plane or information from the D-Plane, and communicates with other C-Plane programs; it realizes machine to machine (M2M) communications. By using the SDN’s API, a new paradigm becomes open; it realizes open M-Plane to the user and realizes optimized network construction for user application programs. The GMPLS protocol is one of the applicable control protocols for realizing the SDN.

5.2 Transport SDN and Software Defined Transport Network (SDTN)

An OpenFlow technology is one of the SDN technologies [56]. One major target of introducing the OpenFlow technology is applying SDN to a data-center network, which requires easy deployment, easy operation, and easy management of the network. The OpenFlow is flow switching based SDN. A flow is defined by using Ethernet interfaces, MPLS and/or virtual local area network (VLAN) paths, and TCP/IP. An OpenFlow switch switches defined flows. A programmable forwarding table in the OpenFlow switch is configured by a centralized controller. A control protocol between controller and switches is called an OpenFlow protocol.

To extend the target of the OpenFlow technology beyond the data-center network, it is required to extend the OpenFlow protocol applicability from packet switching equipment (e.g., Ethernet switches, MPLS routers, and IP routers) to circuit/path switching equipment (e.g., SDH-XCs, ODU-XCs, and OXCs), which is already supported by GMPLS protocols. To do this, the Open Networking Foundation (ONF), which specifies OpenFlow standardization, has defined an open transport switch (OTS) [57], which emulates non-packet switching equipment as an OpenFlow switch. For example, a wavelength path OXC is emulated by making one-to-one correspondence: wavelength and Ethernet VLAN identifier (ID), and capacity of wavelength and capacity of VLAN. From the OpenFlow controller, a VLAN path is set on the OTS and a wavelength path is set on the actual D-Plane of the OXC. By using the OTS, non OpenFlow equipment can be controlled by the common OpenFlow protocol. This method is called a transport SDN.

Several existing communication infrastructures already applied MPLS and GMPLS protocols in the C-Plane [23], [58], [59]. Therefore, as an SDN control protocol, the GMPLS protocol becomes a possible solution. Enhancing the manageability and the operationability of the transport SDN is required to apply the SDN technology to carrier networks and using both GMPLS control protocol and OpenFlow protocol is also required. A framework incorporating both requirements above mentioned is called the software defined transport network (SDTN) [60].

In Japan, SDTN is mainly discussed in the interoperability working group of the research promotion council of Kei-han-na Info-Communication Open Laboratory [61]. The interoperability working group promoted GMPLS interoperability demonstration [33] and recently SDTN interoperability demonstrations, as shown in Fig. 10 [62], Fig. 11 [63], and Fig. 12 [64]. In Fig. 10, virtual transport networks are defined as slices. Each slice is controlled by the GMPLS, MPLS, and OpenFlow protocols. The final target of this demonstration was that all SDN controllers of each slice’s will be co-operated as a unified transport network. In Fig. 11, five-domain transport networks composed of one core network with 100Gbps WDM transmission, two metro networks with 100Gbps optical packet switch-
Fig. 11 Demonstration of five-domain SDTN.

Fig. 12 Demonstration of multi-carrier SDTN domains with one SDTN orchestrator.

6. Devices and Switches for Optical Networks

6.1 Offloading Techniques by Using Optical Layer

In telecom and datacom networks, the processing speed and the power consumption of electronic routers or switches have long been bottlenecks. One solution is offloading data traffic by using a lower-layer network such as MPLS-Transport Profile (MPLS-TP) or WDM network. For example, data for IP services in Internet, which occupy half of the data traffic of a certain telecommunication carrier, are accommodated in WDM networks [67]. The biggest challenge is reducing as much network-operation loads as possible by leveraging the high-speed and transparent mechanism of optical switching technologies.

In current metro networks, a circuit-switching type of ROADM and OXC system based on Wavelength Selective Switch (WSS) or Planar Lightwave Circuit (PLC) switch are deployed. To increase the number of input and output ports and the number of optical paths handed in ROADM and OXC systems, low-cost and high-port-count optical switches are required. On the other hand, in case of frequent traffic fluctuation without statistical multiplexing effects, optical circuit switching (OCS) reduces the utilization of fiber resources due to the coarse switching granularity. Optical packet switching (OPS) enables finer network granularity and energy-efficiency because optical signals are finely divided in the temporal domain. Therefore, research and development on OPS have been carried out to achieve higher switching performance [68]–[73].

In near future, a wide variety of contents from small-data-size, low-quality one (e.g., sensor data collection, E-mails) to large-data-size, high-quality one (e.g., high-definition video distribution, remote surgery) will be transported on networks. To efficiently transmit those contents, it is expected to employ suitable transport schemes according to the property of contents. While OCS links enable a fully occupied bandwidth and end-to-end QoS guaranteed data transport, OPS links serve bandwidth-sharing and best-effort data transfer. If OPS and OCS architectures are integrated, both best-effort and QoS guaranteed services can be provided on the same infrastructure. Recently, some research projects have also investigated integrated packet/circuit switching in [65], [74]–[76].

In the following subsections, we present the advanced device and optical switching technologies: a high-density Silicon photonic switch for circuit switching, a hybrid optoelectronic router, and an optical packet and circuit integrated network system.

6.2 Silicon Photonic Switch

For establishing many connections of optical paths in OCS, the key device is a low-cost, high-port-count, and strictly-non-blocking optical switch. Silicon Photonics technology is a promising approach because it allows high-density photonic integration and mass production using a complementary metal-oxide-semiconductor (CMOS)-compatible fabrication process with large wafers.

Recently, an ultra-compact 32 × 32 strictly-non-blocking Si-wire optical switch packaged with a land grid array (LGA) interposer has been developed by National Institute of Advanced Industrial Science and Technology (AIST) [77]. The optical switch integrates 1024 thermooptic Mach-Zehnder (MZ) switches and 961 intersections on a very small, 11 × 25 mm² die. The footprint of the switch chip is 46 times as small as that of a silica-based 32 × 32 optical switch. Figure 13 shows a 32 × 32 1-rack unit blade
switch. The 1024 full path characterization of the $32 \times 32$ Si-wire optical switch has been also reported [78]. On-chip loss and crosstalk in the worst scenario are 14.5 dB and less than $-20$ dB around center wavelength, respectively.

6.3 Hybrid Optoelectronic Switching System

In large data centers (DCs), a huge amount of data is processed in more than ten thousand servers, which are connected with each other via networks. To improve the performance of DCs, high scalability, low-latency and high energy efficiency DC network is necessary.

Recently, a torus-topology photonic data center network based on hybrid optoelectronic routers (HOPR) and an OpenFlow controller has been developed by NTT Device Technology Laboratories [79]. Figure 14 shows the network architecture and the configuration of a HOPR.

The HOPR consists of label processors, an optical switch, an optical fiber delay line (FDL), and an optoelectronic shared buffer that acts as an aggregation switch. Currently, an upgraded HOPR is being developed for that network to support the OPS/OCS/VOCS (virtual OCS) schemes and to handle 100 Gbps optical packets with a significant reduction in power consumption and latency compared to the previously developed 10 Gbps HOPR [73]. Figure 15 shows the photograph of a HOPR under development and the performance goals.

6.4 Optical Packet and Circuit Integrated Network System

An optical packet and circuit integrated (OPCI) network has been proposed by National Institute of Information and Communications Technology [65]. Figure 16 shows the concept of an OPCI network and the configuration of an OPCI node. The use of OPS and OCS links, having flexible modulation format and wavelength slot, enables effective network resource allocation of heterogeneous applications, such as bursty or huge-capacity data transmission. Additionally, depending on the traffic conditions, a boundary between OPS and OCS wavelength resources can be independently allocated.

Figure 17 shows the configuration of the latest $2 \times 2$ OPCI node system for ring networks [80]. It mainly consists of two subsystems for ROADM and OPS switching. The ROADM subsystem has seven on-off-keying (OOK) 10G OTN transponders, and two 100G OTN transponders with dual-polarization quadrature phase-shift keying (DP-QPSK) format. The OPS subsystem has a 100G OP transponder. To realize multi-format optical switching, burst-mode ED-FAs with optical feedback and low polarization dependent
loss (PDL) electro-absorption (EA) optical switches with low patterning effect are used. Error-free switching of simultaneous 100 Gbps DP-QPSK/OOK optical packets and circuits has been demonstrated.

Moreover, an OPCI network testbed consisting of three OPCI nodes has been deployed in the Tokyo metropolitan area, as shown in Fig. 18. Two nodes are in NICT Headquarters, Koganei and one node is installed in NICT Otemachi near Tokyo Station. The fiber and distance between Koganei and Otemachi are around 44.5 km field-installed single-mode fiber (SMF) and 6.5 km dispersion-compensating fiber (DCF). The operation trial of the OPCI network testbed that provides access to the Internet has been demonstrated [81]. Figure 18 also shows the average bit rate for 30 minutes in eight days and for five minutes in one day about the Internet access via the OPCI network between the LAN and the Internet. The OPCI nodes stably worked during the demonstration. The network testbed is expected to accelerate near-future network development.

7. Development of Optical Networks and Future Directions

This section addresses advances in networking technologies and future direction on optical networking.

7.1 Advances in Network Technologies

Figure 19 shows a brief overview of network advances, together with characteristic movements in network development, which is detailed in the following subsections.

7.1.1 Universal Standard

Networks installed before 1990 are based on the ple-
synchronous digital hierarchy (PDH). The asynchronous nature of this multiplexing scheme creates several difficulties with significant processing overheads and inefficiencies. The digital hierarchies of Europe, North America and Japan are different, as shown in Fig. 19. In 1990, SDH NNI standards were developed at International Telegraph and Telephone Consultative Committee (CCITT), which is presently International Telecommunication Union-Telecommunication Standardization Sector (ITU-T). Thus, the network is completely synchronized, and direct multiplexing/demultiplexing of transmission signals can be easily performed through any network device. In addition, any low-speed multiplexing level signals can be accessed so digital cross-connect functionalities and transmission signal monitoring capabilities are more easily implemented. A telecommunication network can, therefore, be handled as just a single digital circuit pack, and advanced network functions can be realized simply. The technique has become the foundation on which core and metro networks have been built throughout the world (the variant used in North America is called SONET) [82]. Developed for the access network part, the narrowband integrated services digital network (N-ISDN) was expected to replace the existing analog subscriber transmission systems and so converge the huge number of variations in the world. N-ISDN was soon replaced with more recent developments, but N-ISDN and SDH/SONET were recognized universally as next step standard technologies, based on which access and core networks were deployed.

7.1.2 IP Convergence and Divergence of Architectures and Technologies

In the early 2000’s, the Internet began its world penetration, and core IP router throughput reached that of SDH/SONET XCs owing to the architectural change and utilization of ASICS, and then IP convergence started-everything on IP, IP on everything. Until 2005, the technology alternatives were extremely varied and this yielded networks optimized for each country’s or region’s or carrier’s situation. Death of the monopolies and enhanced competition strongly drove the optimization of architectures and technologies according to the different physical/geographical and regulatory situations in the world. Extensive choices have become available through rapid technical advancements. They include the advent and penetration of IP, new technical developments such as optical WDM networking technologies that use wavelength routing, rapid advances in access technologies, the emergence of IP-based control protocols, and MPLS/GMPLS, all of which provide powerful tools for creating the next generation networks that support IP convergence. For example, in core networks, the integrated or separated network approach for provisioning of legacy(voice/data) and Internet services had been adopted. Digital cross-connect system (DXC)-based mesh or concatenated ring architecture was used. In metro networks (particularly those of North America), different architectures co-existed; IP Centric Architecture, where the MPLS router, Ethernet switches, and voice-over-IP (VoIP) routers are utilized; SDH Centric Architecture, where Add-drop multiplexer (ADM)/DXC and MPLS router are utilized; and ATM Centric Architecture, where ADM/DXC, ATM cross-connect, and remote digital subscriber line access multiplexer (DSLAM) are utilized. In access networks, fiber to the home (FTTH) formed both single star architecture (with media converters) and double star configuration using Ethernet switch, ethernet passive optical network (EPON), and Gigabit-capable PON (GPON)/Broadband Passive PON (BPON). Thus, IP became the major vehicle for information transport, but the network architecture and the technologies utilized showed wide variations around the world.

7.1.3 Integrated Control Plane and Integrated Node System

Around 2010, various integration technologies were developed. Up to that point, technical advances allowed us to uti-
lize different sets of network elements. However, in order to strengthen scalability, manageability, and cost-effectiveness, new technologies are required. In terms of control and architecture, fixed mobile convergence started using the 3rd generation partnership project (3GPP) IP multimedia subsystem (IMS) and session initiation protocol (SIP), and automatically switched optical network (ASON)/GMPLS based automated transport system connection provisioning were introduced in some countries. Regarding transport, wavelength routing using ROADMds began to be utilized in linear and ring-based architectures; electrical level transparency was enhanced by OTN (G.709/Digital Wrapper), which effectively accommodates STM level-N (STM-N), 10 Gb Ethernet, and Gb Ethernet signals. Existing SDH/SONET have been extended to next-generation SDH (NG-SDH)/SONET, where generic framing procedure (GFP), virtual concatenation (VCAT) and link capacity adjustment scheme (LCAS) functions have been developed to enhance transport flexibility. The converged packet optical transport platform that has been deployed integrates WDM, OTN, MPLS-Transport Profile (MPLS-TP), and Ethernet. A software configured equipment interface, including programmable transport line module that can accommodate STM-N, Gb Ethernet, Fiber Channel, and Fast Ethernet, was developed. Enhancement of network manageability with improved flexibility has been sought.

7.1.4 Network Paradigm Shift

Around 2015, a network paradigm shift became clear. Internet traffic became dominated by that relating to hyper-giant contents holders including over the top (OTT) video service providers, and cloud networking services and contents delivery network (CDN) advanced. In this context, one notable point in network development is that metro traffic, which remains within the metro area, surpassed core network traffic in 2014 throughout the world, and is expected to grow nearly twice as fast as core network traffic [83]. This is spurred by data center development in metro areas and the advancement of CDNs. SDN/network functions visualization (NFV) and open interface (OpenFlow) technologies are being eagerly developed to allow not only network providers but also network users to control their networks to suit their own goals.

The paradigm shift spurred traditional communication service providers to be more of contents service providers, and in this context capacity can be regarded as a cost rather than a means to cultivate new revenue. As a result, R&D activities in most of the major carriers shifted to the development of new services rather than new systems and hardware technologies. Network technologies driven by wide-spread and upcoming services and applications including M2M and Internet of Things (IoT) should be explored.

7.2 Future Directions on Optical Networking

Among the network advances discussed above, let us look at optical technologies in core/metro networks. Optical fiber transmission was first introduced in the early 1980’s and fiber transmission capacity increased continuously by around 50% a year through the introduction of various innovations such as single-mode fibers, Erbium-doped fiber amplifier (EDFA), WDM, and digital coherent technologies [84]. Point-to-point optical transmission evolved into optical routing using OXC/ROADM in the early 1990’s [12]–[15], [85]. At that time the number of available WDM wavelengths per fiber was relatively small, 8-16, and hence PLC devices were utilized. Later, as available wavelengths per fiber increased, the PLC was replaced by WSSes based on 3-dimensional spatial optics.

Optical networking technologies are now mostly applied to just core and metro-core networks, but in the future they will expand deeper into metro networks, up to metro access, as metro traffic dominates more and more. The envisaged advances in optical networking technologies are summarized in Figure 20. The requirements are different from core and metro networking. Given this background, large port count and cost-effective OXCs/ROADMs are essential [86]. They are needed for grooming in the optical-path layer, as grooming in the electrical layer, the current approach, is not always efficient. Such optical switches can be a key component in realizing optical-path layer protection/restoration and optical-path layer services including optical circuit switched services, which can create new revenue generating services. Toward this goal, various studies have been addressed so far to realize efficient switch architectures for creating large scale OXCs [87]. It has been proven that even if we slightly limit the node routing capability, but adopt an intra-node blocking aware RWA algorithm, the offset in network routing performance is minimal and the available hardware reduction can be enormous [88], [89]. Creating cost-effective large port count optical switches will also innovate intra-data-center networks, where optical technologies are now used merely for point-to-point transmission. Some details are presented in [90]. Optical technologies, which can be much more energy efficient than elec-
trical ones at high bit rates, will be used within systems in data centers and for high-performance computing for interconnections among packages, on-board devices, and large scale integration devices (LSIs), where Silicon photonics will play a key role [91]. It will be very difficult to apply optical technologies for deep processing as has been done in electrical systems. However, a lot of opportunities are seen if adequate innovations in device and system technologies are achieved, some of which are addressed herein.

The current optical fiber transmission faces a number of limitations. The fiber capacity limitation can be mitigated by elastic optical networks (EONs) [92]–[94]. EONs have the potential to allocate spectrum to optical paths according to the capacity requirements of client signals, where the entire spectrum will be divided into narrow frequency slots and optical connections will be allocated a different number of slots [95]–[97]. Furthermore, EONs can allocate the number of frequency slots depending on the modulation format of each client signal that can be adapted to the transmission distance and so on [98]–[101]. As the result, EONs can efficiently accommodate optical paths with high symbol rates and higher-order modulation formats, and hence network utilization efficiency can be improved compared to current fixed grid optical networks. However, the passband shape of WSSs in a ROADM/OXC node cannot be ideal, which causes serious signal degradation in the course of optical routing; i.e. spectrum narrowing. This degradation accumulates with each node traversed by the optical path, and hence a broad guard-band needs to be inserted between adjacent paths. To minimize the bandwidth wastage due to the guard-bands, the coarse granular routing schemes have been proposed and analyzed in detail, which includes hierarchical optical path networks introducing waveband paths [17], [102], grouped routing networks [103], [104] that utilize GRE (Grouped Routing Entity) pipes, and coarse/fine hybrid granular routing networks that employ virtual direct links [105]. Optical paths are densely packed with minimum spacing in each group, while an enough guard-band is inserted only between adjacent groups. This minimizes spectrum narrowing effects and improves spectral efficiency simultaneously. Thus the dilemma between the guard-band reduction and the spectrum narrowing mitigation can be resolved.

When traffic increases, multiple fibers are needed to connect adjacent nodes, or spatial division multiplexing (SDM) is utilized. For this, multi-core fibers or multi(few)-mode fibers may provide a cost effective solution in the future. Extensive studies [106], [107] are being addressed on this, while the wide deployment will be seen when the overall cost of multi-core fibers and the related technologies including multi-channel optical amplifiers, parallel optical switch elements, connectors, and opto-electronics integration becomes competitive with single core systems.

8. Conclusions

The optical networking paradigm is an emerging research area for high-speed transmission. This paper has introduced and discussed the past and recent trends of optical networks and addressed the future directions.

We started with the basic concept of the optical network and then turned into path networks with the historical backgrounds and trends. Path networks with various multiplexing technologies, such as time-division multiplexing (TDM), asynchronous transfer mode (ATM), and wavelength-division multiplexing (WDM) were detailed. Immediately after the discussion on path networks, our discussion focused on the multi-generalized protocol label switching (GMPLS) technology. Next, we looked into the multi-layer traffic engineering and a path computation element (PCE). Multi-layer traffic engineering designs and controls networks considering resource usages of more than one layer, which leads to use network resources more efficiently than the single-layer traffic engineering adopted independently for each layer. Then we moved into software-defined networks, which put the designed network functions into the programmable data plane by way of the management plane. In addition, we described the evaluation from GMPLS to software defined networking (SDN) and transport SDN. The essential devices and switching technologies that have been developed and deployed for optical networks were addressed in this paper. Finally, the future development of optical networks, including advances in networking technologies, was addressed by highlighting the future directions.

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Eiji Oki is a Professor at Kyoto University, Kyoto, Japan. He received the B.E. and M.E. degrees in instrumentation engineering and a Ph.D. degree in electrical engineering from Keio University, Yokohama, Japan, in 1991, 1993, and 1999, respectively. In 1993, he joined Nippon Telegraph and Telephone Corporation (NTT) Communication Switching Laboratories, Tokyo, Japan. He has been researching network design and control, traffic-control methods, and high-speed switching systems. From 2000 to 2001, he was a Visiting Scholar at the Polytechnic Institute of New York University, Brooklyn, New York, where he was involved in designing terabit switch/router systems. He was engaged in researching and developing high-speed optical IP backbone networks with NTT Laboratories. He was with The University of Electro-Communications, Tokyo, Japan from July 2008 to February 2017. He joined Kyoto University, Japan in March 2017. He is an IEEE Fellow.
Naoya Wada received the B.E., M.E., and Dr.Eng. degrees in electronics from Hokkaido University, Sapporo, Japan, in 1991, 1993, and 1996, respectively. In 1996, he joined the Communications Research Laboratory, Ministry of Posts and Telecommunications, Tokyo, Japan, where he conducted research on optical packet switching (OPS), optical processing system, burst-mode optical communication technologies, huge capacity optical transmission based on multi-core fiber. He is currently Director General of Network System Research Institute, NICT. He is a member of the IEEE Communications Society, IEEE Photonics, IEICE, the Japan Society of Applied Physics, and the Optical Society of Japan.

Satoru Okamoto is a Project Professor of the Keio University, Kanagawa, Japan. He received his B.E., M.E. and Ph.D. degrees in electronics engineering from Hokkaido University, Hokkaido, Japan, in 1986, 1988 and 1994. In 1988, he joined Nippon Telegraph and Telephone Corporation (NTT), Japan, where he conducted research on ATM cross-connect system architectures, photonic switching systems, optical path network architectures, photonic network management systems, and photonic network control technologies. He is now researching future IP+ optical network technologies, and application over photonic network technologies. He was an associate editor of the IEICE Transactions on Communications (2006–2011) as well as the chair of the IEICE Technical Committee on Photonic Network (PN) (2010–2011), and was an associate editor of the Optical Express of the Optical Society of America (OSA) (2006–2012). He is an IEEE Senior Member.

Naoaki Yamanaka graduated from Keio University, Japan where he received B.E., M.E. and Ph.D. degrees in engineering in 1981, 1983 and 1991, respectively. In 1983 he joined Nippon Telegraph and Telephone Corporation’s (NTT’s) Communication Switching Laboratories, Tokyo Japan. He has been active in the development of ATM base backbone network and system including Tb/s electrical/optical backbone switching as NTT’s Distinguished Technical Member. He moved to Keio University in 2004. He is currently a Professor in Dept. of Information and Computer Science, Keio University, Japan, Vice Chair of Keio Leading-edge Laboratory of Science and Technology and chair of Photonic Internet Labs. He is an IEEE Fellow and an IEICE Fellow.

Ken-ichi Sato received his B.S., M.S., and Ph.D. degrees in electronics engineering from the University of Tokyo, in 1976, 1978, and 1986, respectively. He is currently a Professor at the Graduate School of Engineering, Nagoya University, and he is an IEEE and NTT R&D Fellow. Prof. Sato is a Fellow of the IEICE. He received the Young Engineer Award in 1984, the Excellent Paper Award in 1991, the Achievement Award in 2000, and the Distinguished Achievement and Contributions Award in 2011 from the IEICE of Japan, and the Best Paper Awards in 2007 and 2008 from the IEICE Communications Society. He was also the recipient of the Distinguished Achievement Award of the Ministry of Education, Science and Culture in 2002, and the Medal of Honor with Purple Ribbon from Japan’s Cabinet Office in 2014.