Photonic Network Vision 2020—Toward Smart Photonic Cloud

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(Invited Tutorial)

***Abstract*—A vision of the photonic network in 2020 is presented, which envisages a "smart photonic cloud." A smart photonic cloud is defined as a universal network platform without any physical or logical constraint that provides flexible connectivity for machine-to-machine communication such as networked high-performance computing or intra- and inter-data center networks. The key requirements for the network in the Big Data era include an ultralarge capacity with low power consumption, low latency, as well as flexibility on demand to the changes in the configuration and bandwidth of the optical path. To cope with the growing demand for network virtualization, novel photonic layer virtualization will be proposed, which differs from the conventional approach in terms of the number of slices and the dynamic range of the bandwidth of each slice. First, the objectives and the guiding principle of the vision will be addressed. Next, three "Ss" will be presented that represent the key enabling technologies, namely scale-free photonics, smart photonic networking, and a synthetic transport platform. A key engine with which to realize the above three enabling technologies is the photonic network processor (P-NP), which can define versatile functionality of switches and transmission systems by software. The P-NP takes advantage of the rapid progress made on digital signal processing for coherent optical transmission systems, and it consists of pools of optical frontends, digital signal processors, L1/L2 switches, which are either electrically or optically interconnected based on silicon photonic technology. Finally, a multifunctional optical cross-connect and a bit-rate-flexible optical transponder are presented as examples of P-NP applications.**

***Index Terms*—Digital signal processing (DSP), network virtualization, optical fiber communications, photonic network, photonic network processor.**

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I. Introduction

THE photonic network will play a crucial role in the coming Big Data era. Commerce, medical care, education, entertainment, and social life will rely more heavily on cloud computing in the near future. Data are generated from various sources such as sensor networks, scientific meteorological simulations, genomics, computational physics, financial transactions, social network services, and the Internet logs of search engines. The network traffic for storing, updating and accessing to all those generated data sets in the data centers (DCs) is exponentially increasing. According to the Cisco white paper, DC traffic will reach 6.6 zetta-bytes by the end of 2016 with a compound annual growth rate (CAGR) of 31% [1].

In the Big Data era, we can mine valuable information from data like extracting rare metals from used appliances. The analysis of Big Data, based upon real-time complex event processing, will be performed by exchanging huge quantities of data on inter-DC and intra-DC networks [2]. The size of data sets that are feasible to be processed in a reasonable amount of time is often limited by not only the processing capability but also the bandwidth and the latency of data transfer over the networks. Therefore, the network will require an abundant bandwidth with low latency.

Another driver of the data traffic increase will be mobile phones. According to a recent survey, the number of mobile-connected devices will exceed the world's population in 2013 [3]. Overall mobile data traffic is expected to grow to 11.2 exabytes per month by 2017, which amounts to a 13-fold increase over 2012 at a CAGR of 66%. The data rate of mobile access increased 1600-fold over 15 years since 1995. In 2017, the introduction of LTE-advanced will allow the peak rate of mobile phones to reach 1 Gb/s. The peak bit rate of mobile phones has been catching up with the current wire-line access bandwidth over the last 7 years, and this trend will continue in the future. Therefore the impact of the rapid traffic growth over mobile phones on the core network will become more significant in the coming years, and photonic network technologies will play a more important role in mobile backhaul networks.

For the network operators, the cost reduction is the crucial issue to be profitable under a strict price cap of their services, while they have to solve a problem of the capacity crunch caused by the ever-increasing data traffic in the Big Data era. The reduction of operational capital expenditure (OPEX) also remains to be tackled. Current network operation and management (OAM) is labor intensive. For example, if there is need to upgrade the transmission capacity of a link, workers are sent to the sites to exchange the module or card of the OTPs. The operation will incur labor cost and time, say, several hours or more, excluding the several weeks needed to prepare additional modules. Optical paths are currently set up manually by changing the cross-connect connections on site, and hence this also incurs labor cost and takes a long time. If the OTP can be automatically upgraded by updating software from a remote site, and if the switch can be automatically configured, OPEX can be saved, and the time for service delivery can be minimized. Finding a way to reduce the OPEX would make the photonic network less labor intensive. A key to finding the solution is "smartness," namely the capability to synthesize desired switching and transmission functions by software control.

This paper presents a vision of the photonic network in 2020, which envisages a "Smart Photonic Cloud (SPC)." The key requirements for the network in the Big Data era include ultra-large capacity with low power consumption, low latency and flexibility in response to demand for changes in the configuration and bandwidth of optical paths. To satisfy all these requirements, the SPC will establish a universal network platform without any physical or logical constraint, thus providing flexible connectivity for machine-to-machine communications such as networked high-performance computing on intra- and inter DC networks. Also, to cope with the growing demand for network virtualization, the SPC will pursue virtualization technologies in the photonic layer, which will greatly improve on the conventional approach in terms of the number of slices and the dynamic range of the bandwidth of each slice.

The objectives and the guiding principle of the vision will be addressed in Section II. Section III presents three "Ss", which are the key enabling technologies, namely scale-free photonics, smart photonic networking, and a synthetic transport platform. A key engine with which to realize the above three enabling technologies is the photonic network processor (P-NP), which can provide the software-defined versatile functionality of switches and transmission systems. The concept and the detailed architecture of P-NP will be shown in Section III-C. Section IV is devoted to some applications of P-NPs, and Section V provides our concluding remarks.

II. Objectives and Guiding Principle Behind Smart Photonic Cloud

A. *Current Status of Photonic Network Technologies*

Optical fiber transmission capacity has exhibited a constant 100-fold increase every 10 years thanks to WDM-based optical transmission technology. The recent innovation of digital coherent optical transmission technology appears capable of maintaining this trend for another decade [4], [5]. With digital coherent technology, the transmitter can generate light signals of any shape with the combination of digital signal processors (DSP) and ultra-high speed digital-to-analog converters (DAC). This makes it possible to design an ideal filter for Nyquist WDM and to generate accurate M-ary quadrature amplitude modulation (QAM) signals with pre-distortion emphasis. On the receiver side, the optical signals are converted into parallel digital electrical signals by analog-to-digital converters (ADC) and then processed by ultra-high speed DSPs. The DSP at the receiver compensates signal impairments due to the chromatic and polarization dispersion and the nonlinearity of optical fiber. The pre-distortion emphasis at the transmitter can compensates nonlinearity of modulator as well as the impairments caused in the fiber propagation. It then becomes possible to realize such functions as optical polarization tracking and optical phase compensation [6], [7]. Long-haul 100 Gb/s digital coherent transmission systems with dual-polarization quadrature phase-shift keying have already been deployed [8], [9], and the next target bit rate per superchannel will range from 400 Gb/s to 1 Tb/s [10], [11]. Ultra-dense WDM such as super-channel or Nyquist WDM [12] will be the key technology as regards improving spectral efficiency. Emerging space-division-multiplexing (SDM) technologies using multi-core fibers or multi-mode transmission technique are also being extensively investigated to further expand the potential of optical fibers [13].

As the total fiber transmission capacity increases, the technologies for dividing the capacity into many flexible paths are also evolving. One such technology is packet optical transport, where electric packet switches are integrated with WDM optical cross-connects to create flexible sub-wavelength paths with arbitrary bandwidths [14]. Another emerging technology is the flexible grid WDM where the bandwidth of each wavelength can be flexibly adjusted. To allow the efficient allocation of optical spectral bandwidth, a flexible WDM grid has been proposed, which defines a set of nominal central frequencies, a smaller channel-spacing and the concept of a frequency slot [15]. A data plane connection can choose modulation formats and variable-sized frequency slots suitable to the data rate and spectral efficiency to achieve [16].

At the network resource control and management level, network virtualization and software-defined networks quickly become the key concepts in terms of fully utilizing the expanding optical network capacity and path bandwidth flexibility. These technologies enable us to flexibly and efficiently build various dedicated application-specific networks on a single transport network infrastructure, application by application [17].

B. *Objectives of Smart Photonic Cloud*

Although these emerging photonic technologies provide us with ways to continuously expand and fully utilize the potential of optical fiber, the speed of the increase in network throughput or network power reduction seems slow compared with the speed at which photonic technology is evolving. This is because the current IP-based network architecture for data communications is basically a hierarchical multi-hop network of electrical routers or Ethernet switches and such flexible optical paths are only considered to be the "links" between them. The above approach strongly relies on the large-capacity core routers at the top of the hierarchy to route most of the data traffic, and thus the power consumption of expensive state-of-the-art core routers constitutes a bottleneck as regards total network performance and network power reduction, and even network CAPEX/OPEX reduction.

Recently some networks have started to use optical paths or packet-optical paths to off-load heavy router traffic and to reduce the capacity required for the top routers [14], [18]. However, since the amount of data traffic continues to increase exponentially as stated in Section I, this technique cannot be the final solution. Novel network architecture is needed to overcome the limitations of the current router-based networks.

For this reason Photonic Network Vision 2020 has proposed the SPC, which is a universal network platform consisting of full-programmable and scalable photonic nodes. The objectives of the SPC are threefold.

1) Objective 1—Bottleneck-Free Infrastructure: The SPC should be free from the limitations of the large-capacity routers. By fully exploiting the progress made on optical transmission technologies, the network capacity of the SPC can be increased to support any level of demand from network operators or users. On a common transport infrastructure, they can overlay any size of multiple application-oriented network, including ubiquitous sensor networks, machine-to-machine communications, Exa-scale computing [19], or networks for "the Internet of Things" that provides everything with Internet connectivity [20]. Also the network power consumption can be greatly improved by eliminating power consuming large-capacity routers from the network core.

2) Objective 2—Smart and Value-Creative Network: The SPC should have not only unlimited network resources but also the "smartness" of flexibly and efficiently utilizing the network resources to realize value-creative application-oriented networks. This includes the ability to efficiently slice the network resources and dynamically create virtual networks with any topologies and the flexibility to create or modify any network functions such as packet filtering and forwarding, actions at failure events or network storage services as well as the optical transceiver specifications. Moreover, the SPC will be used in an attempt to create novel data-flow transfer methods with low-latency and low-power consumption, by exploiting future photonic switching technologies.

3) Objective 3—Fully-Synthetic Photonic Platform: The SPC establishes a universal network platform where network operators can fully synthesize any networks with any functions required for applications and immediately deliver them to the users. Recent technologies such as the software defined networking (SDN) [21] and network functions virtualization (NFV) [22] proposes creating virtual networks or virtual network functions by effectively using the programmability of current routers or layer-2 switches, such as routing tables or controller software. The SPC extends this direction further to the programmability of entire transport networks by including functions determined by

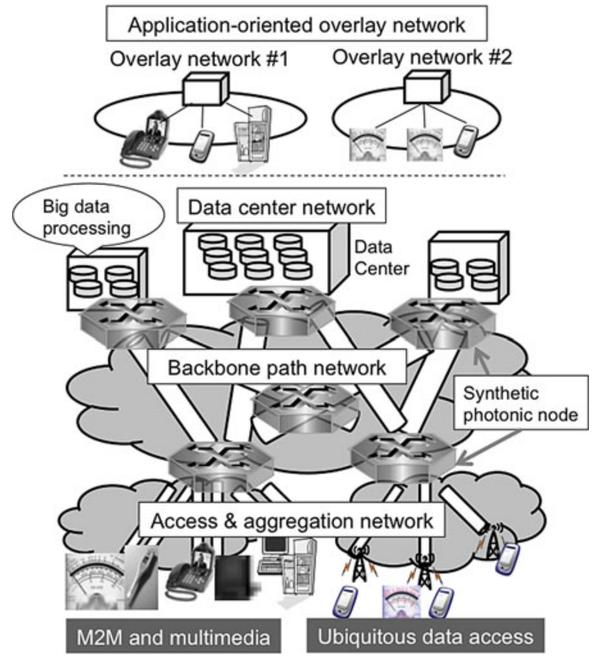


Fig. 1. Conceptual schematic of the Smart Photonic Cloud (SPC) for the Big Data era in 2020. A backbone path network consisting of synthetic photonic nodes that interconnects data center networks and access and aggregation networks with flexible optical L1/L2 paths. Various application-oriented overlaid networks are created on it.

hardware. This enables the operators to fully synthesize and customize the lower layer optical transmission specifications in the transport nodes, such as optical signal baud-rates, modulation formats, noise reduction algorithms in optical transceivers as well as the higher layer features such as the transport protocols, and packet filtering or data storage functions. This platform will reduce the network CAPEX/OPEX because the network operators can efficiently utilize the unused transport node resources already in the field to construct a new overlay application-oriented network, and it can reduce the labor cost required for installing new equipment or replacing the packages on the deployed transport nodes and the cost for maintaining stocks of a wide variety of spare packages.

C. Guiding Principle

The basic idea behind achieving the above three objectives with SPC architecture is to replace the core of the current hierarchical router networks with a flat network consisting of innovative photonic transport nodes called "synthetic photonic nodes". A synthetic photonic node can handle both optical paths realized by fully exploiting the progress made on optical transmission technologies and sub-wavelength paths or logical paths based on novel Layer-2 technologies. And it can also support various higher-layer protocols and user-defined node functions. All these node functions can be synthesized by software.

The network architecture of SPC in Fig. 1 is very simple: the backbone path network at the center consisting of synthetic photonic nodes interconnects the DC networks at the top and the access and aggregation networks at the bottom with direct optical paths realized by the photonic nodes. The access and aggregation networks aggregate and distribute data packets from fixed or mobile network users' devices or distributed machines or sensors, while the DC networks aggregate and distribute data packets from a huge number of servers and storage facilities. Since the amount of aggregated traffic in each of the access and aggregation networks and the DC networks increases as the Big Data era approaches, the capacity required to interconnect them is sufficient to allocate a direct optical path. Therefore, the multi-hop network of electrical large-capacity routers is not necessary for the backbone. A flat network consisting of innovative photonic transport nodes, which have the programmability in the node functions including higher-layer functions and efficiently handle optical paths, is much more suitable for the backbone and reduces the network latency and power consumption. In the access and aggregation networks and the DC networks, the key function is efficient packet-by-packet data aggregation and distribution, and electrical routers and layer-2 switches will be useful even in future networks. However, future optical switching technologies that extend passive optical networks (PON) and high-speed optical packet switching will be also effectively used to offload electrical switches.

The entire SPC is managed by an integrated virtual network operation extending SDN and NFV capabilities, and the operators can dynamically create and efficiently manage the overlaid networks with various application-oriented functions. Photonic network vision 2020 proposes the investigation of the three key technologies to realize this SPC architecture: scale-free photonics, smart photonic networking, and a synthetic transport platform. These are called the three "Ss" technologies and the challenges of each technology are described in detail in Section III.

III. Three "Ss" Key Enabling Technologies

The three "Ss", technologies which are key enabling technologies that all start with the letter S, namely scale-free photonics, smart photonic networking, and synthetic transport platform, will be discussed. The three "Ss" technologies serve as the bases for creating the SPC.

A. Scale-Free Photonics

Scale-free photonics represent the technologies to overcome the physical limitations in the optical transmissions. They include challenges involved in further expanding the optical transmission capacity limit as well as arbitrarily slicing the capacity into any number of channels as the basis of a bottleneck-free infrastructure. As regards the fiber capacity limit, SDM technologies such as multiple cores per fiber or multi-mode transmission will increase the total capacity per fiber, but the challenge of improving the spectral efficiency per core remains important. Ultra-DWDM such as super-channel or Nyquist WDM [12] will be the key to improving the spectral efficiency, where the target is a total transmission capacity of several tens to a hundred Tb/s per single core. Technologies for stabilizing frequency of the light source and reducing noise are also the basis for achieving this goal.

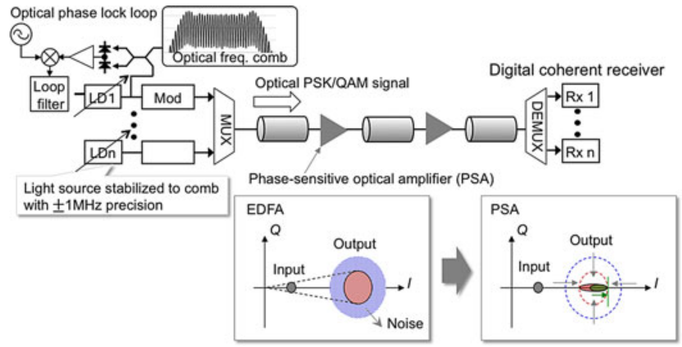


Fig. 2. In-line phase-sensitive amplifier (PSA) in a trunk line along with a frequency-stabilized optical transmitter using optical phase lock loop.

As for frequency stabilization, a frequency-stabilized laser is essential as the transmitter for coherent transmission systems, particularly Nyquist WDM. In the future it may be possible to deliver optical frequency and phase references to transmitters and receivers at remote sites through a frequency-synchronous network on a global scale and calibrate the light source and local oscillator on site. As shown in Fig. 3 the optical frequency comb generator and optical phase lock loop will be promising for use in the calibration [23]. The target light source frequency accuracy for 2020 is ± 1 MHz, and the target linewidth of the light source is less than 10 kHz.

As regards the noise reduction, an optical amplifier with a low noise figure (NF) is attracting attention. The low NF of an in-line optical amplifier improves the optical signal-to-noise ratio in long-haul transmission systems, resulting in an extension of the repeater span. The resulting reduction in the number of the amplifiers has a great impact on the system cost and power consumption. Toward 2020 and beyond, the challenge will be to develop an ultimately low NF in-line optical amplifier such as a phase-sensitive amplifier (PSA). As shown in Fig. 2 the theoretical NF of an ideal optical PSA is 0 dB [24]. Recently, the PSA has exhibited low noise characteristics and a waveform shaping effect for PSK and QAM signals [25].

Technologies designed to reduce the noise generated by the correlation between multiple channels has become very important, since new transmission technologies use multiple channels or superchannels to transmit ultra-broadband data. If we are to improve spectral efficiency, we need higher-level QAM signals and ultra DWDM signals without a "spectral gap" between adjacent channels, e.g., Nyquist WDM. Advanced DSP and higher-speed DAC/ADC are needed to realize Nyquist WDM and a multilevel QAM of more than 16. To expand channel capacity, superchannel transmission technologies [26] with multiple subcarriers have been actively investigated for next-generation signals beyond 100 Gb/s such as dual-subcarrier PDM-16QAM. In addition, SDM technologies utilize spatially overlapped signals (e.g., spatial superchannel [27]) with the same wavelength in multi-core and multi-mode fibers. However, such superchannel techniques are very sensitive to linear/nonlinear crosstalk between adjacent channels and

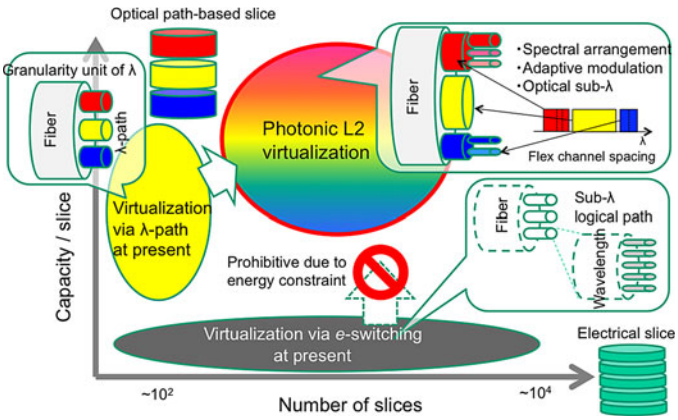


Fig. 3. Capacity per slice as a function of the number of slices for conventional virtualization using electrical and wavelength paths. Photonic layer 2 (P-L2) virtualization fills the vacancy of conventional virtualization techniques.

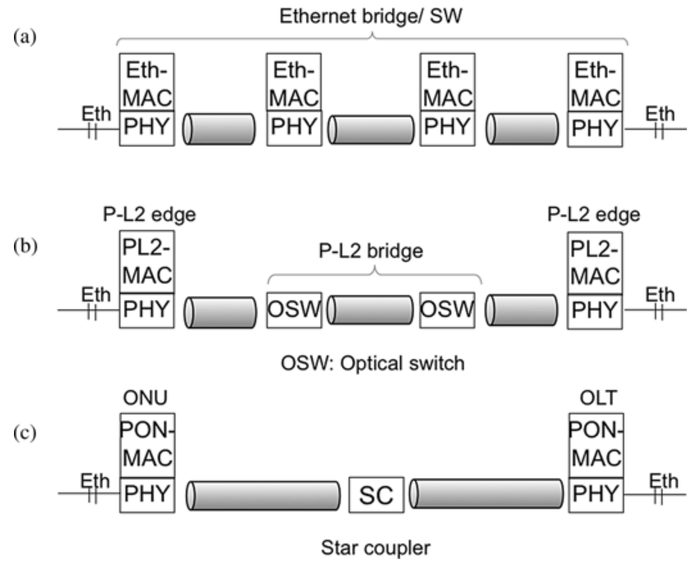


Fig. 4. Comparison of network architecture. (a) Multi-hop Ethernet switch network, (b) photonic layer 2 (P-L2) network, and (c) Ethernet passive optical network (PON).

between spatial modes, and so advanced techniques for reducing crosstalk will be indispensable. In previous studies [28], [29], inter- and intra-channel nonlinear crosstalk compensation using a multiple-channel digital back propagation algorithm [30] was demonstrated and a Q-factor increase of more than 1 dB linear crosstalk compensation between 6 spatial modes using 12×12 multiple-input multiple-output (MIMO) was also demonstrated [31]. However, in these demonstrations, MIMO DSP was performed off-line by using digital sampling oscilloscopes with several input channels. To realize a real-time MIMO DSP for crosstalk compensation, cooperation between multiple DSP-LSIs and advanced DSP algorithms [32] is essential.

B. Smart Photonic Networking

Smart photonic networking refers to technologies that fully incorporate the layer-2 networking functions into photonic nodes and effectively utilize the transport network resources for smart and value-creative networks. This is what "smartness" means. Fig. 3 shows the capacity per slice vs. number of slices in the network virtualization. Network virtualization is currently performed mainly in the electrical domain. It can provide a large number of slices, for example ten thousands. But each slice is thin due to the limit of the total throughput of an electrical switch. On the other hand, an optical path-based slice has a problem in that the number is limited to a hundred.

What differentiates "photonic layer-2 (P-L2)" virtualization from the legacy virtualization is that we can increase the number of slices and extend the dynamic range of slice capacity, owing to the flexible spectral arrangement and sub-wavelength path. Future photonic nodes incorporating technologies such as digital coherent optical transceivers and flexible grid WDM can create optical paths with arbitrary bandwidths over a large dynamic range of around 30 dB ranging from 1 Gb/s to 1 Tb/s, which enable us to utilize the fiber capacity in the SPC flexibly and efficiently. By integrating the layer-2 networking functions into the photonic node, it can divide the bandwidth of each wavelength into many logical paths with narrower bandwidths without using external electrical packet switches.

Due to the combination of both flexible wavelength-based "physical" paths and packet-based sub-wavelength "logical" paths, the virtual network slices in the SPC outnumber those of the conventional WDM-based virtual networks where only up to 100 wavelengths are available on each link as indicated by the direction shown in the top-left of Fig. 3. This is the concept of photonic layer virtualization.

The layer-2 function in the photonic nodes, such as packet forwarding rules including broadcast and multicast or protocols for the address-location resolutions, are programmable from the controller outside the node as in current software-defined networks. This will be the basis for creating virtual slices with various topologies and various data handling operations for application-oriented networks.

Smart photonic networking will also be used to establish P-L2 technology which provides an end-to-end optical connection with ultimately low latency close to the propagation delay. As for the layer-2 networking protocol, Ethernet is widely used in current networks, and Ethernet switches are in widespread use. However, an innovative approach is needed to improve the power consumption and packet forwarding delay of electrical circuit-based switches for the scale-free SPC. The key concept of the P-L2 is to simplify the Ethernet bridging or switching functions as much as possible, by exploiting the inherent nature of photonics and optics such as its high speed, abundant bandwidth, and all-optical processing capability. The intention is to create a new photonic-native data transport protocol, not necessarily emulating the conventional Ethernet protocol, while retaining the interface with the existing protocols at the edges.

Fig. 4 compares the architecture of a P-L2 network with that of an Ethernet. A typical Ethernet is a multi-hop network of Ethernet bridges or switches, in which all data packets are processed by electrical circuits for the physical (PHY) and media access control layers [see Fig. 4(a)]. In the P-L2 architecture, all-optical signal processing is adopted and combined with the digital electronics in such a way that the best of both powers can be fully exploited [see Fig. 4(b)]. At a P-L2 edge, the PL2-MAC layer converts the data packets of the existing protocols such as Ethernet into data signals for P-L2. Also the complicated processing for the layer-2 protocol such as the address-location resolution and the OAM are handled by the electronic circuits in the media access P-L2 edges. In this scheme, the broadcast signals are not used for address resolutions, since they generate heavy traffic and limit the scalability of the network. By employing the software defined network technology, address resolutions are managed by the outside software and signaling, and the routing table in PL2-MAC is fully controlled through the control plane.

The PHY layer in P-L2 edge converts the data signal from the PL2-MAC layer into optical signals for P-L2 and transmits them to a P-L2 bridge over transparent optical channels with a flexible bandwidth of up to one Tb/s. P-L2 bridges transfer the optical data signals from P-L2 edges to their destinations through optical switches, without converting the optical signals to electrical signals. As regards the switching method for optical switches in the P-L2 bridge, not only circuit-based switching using low-speed optical switches but also time-slot- or packet-based switching using high-speed space switches or high-speed tunable lasers will be used to fully utilize the optical transmission capability and to realize data aggregation or distribution in optical region. This P-L2 architecture can build a wide-area layer-2 network with "optically-one-hop" connections.

From another viewpoint, it might be possible to see this P-L2 architecture as a multi-hop version of the Ethernet PON. While a passive optical coupler in the center connects ONUs and an OLT in a PON system [see Fig. 4 (c)], a network of active optical switches connects those edges in a P-L2 network, and the size of the network can be expanded to handle hundreds of edges by using multi-stage optical switches. The preliminary investigations of this direction for P-L2 have already been reported for a time-slot-based optical network [33]. In addition, the technologies studied for optical packet switching might be useful for realizing the P-L2 bridges [34].

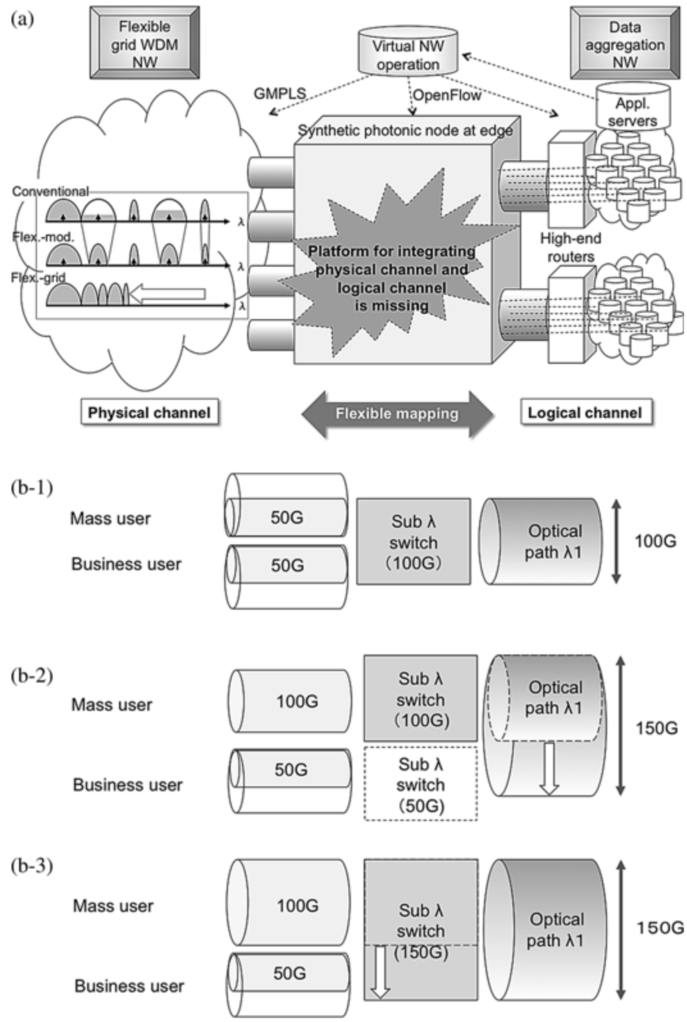
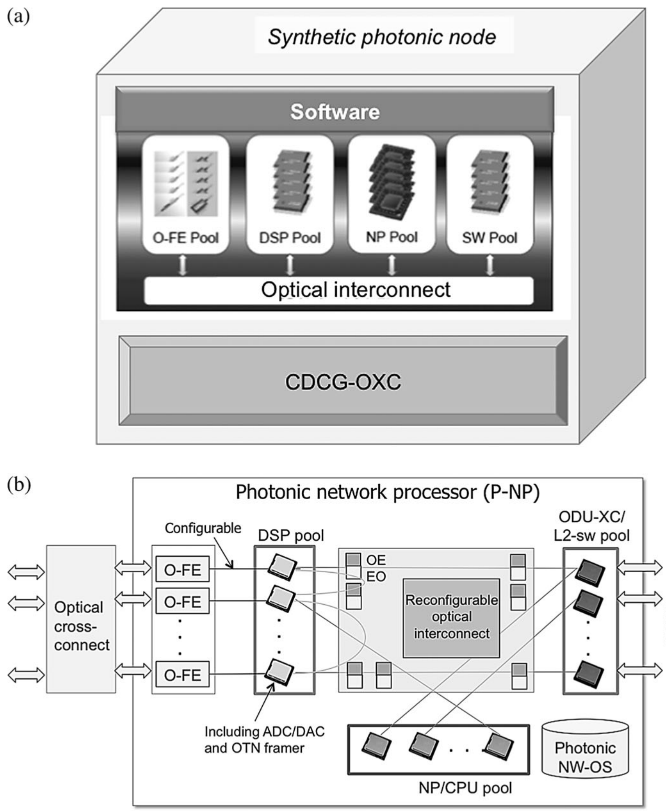


Fig. 5. (a) Contrast between the logical channel of an IP network and the physical channel of a flexible grid WDM transport network where the bridging functionality of flexible mapping technology is currently missing, and (b) upgrade scenario of a sub-wavelength switch when demand arises for another 50 G bandwidth from mass users.

C. Synthetic Transport Platform

Optical paths of 100 G and beyond will soon be available, and a flex grid provides physical flexibility in wavelength allocation. On the other hand, it is well known that the IP network has logical flexibility. What is missing is a bridge between physical flexibility and logical flexibility as illustrated in Fig. 5(a). Here is an example. Suppose the operator provides customers with two 50 G label switched paths of MPLS transport profile or two 50 G Ethernet links by dividing a 100 G wavelength path into two 50 G links using a sub-wavelength (λ) switch as shown in Fig. 5(b-1). When a customer requests another 50 G, the operator can increase the wavelength path bandwidth to 150 G using flex-grid. The sub-wavelength switch should also increase the capacity by adding additional switching modules as shown in Fig. 5(b-2). Finally, both 100 G and 50 G user paths are multiplexed into a 150 G wavelength path via 150 G capacity sub-wavelength switch as shown in Fig. 5(b-3). The operator should immediately respond to the customer's demand. But the scaling-up process takes long. For the operator to immediately respond to the customer demand by bridging the gap between the physical and logical channels, therefore, the future transport node needs scalability, L2 integration, programmability, and common hardware. Currently the sub-wavelength switch, including multiplexing/demultiplexing functions, cannot be expanded from 100 G to 150 G because its capacity is limited to a single chip of LSI such as a 100 G OTN framer, a DSP, and a network processor. To fully exploit the transport capability, layer-2 functionalities such as sub-wavelength switching and client path encapsulation into common layer-2 frame have to be integrated in the transport node. This makes it possible to map sub-wavelength client signals onto an optical path.

A synthetic transport platform is realized with a network of synthetic photonic nodes. A synthetic photonic node is a novel transport node that integrates a next-generation optical cross connect and a fully-programmable "P-NP", which enables us to



(c)

Chip	First stage	Second stage
Optical interconnect	4-channel x25 G	16-wavelength x 25G
DSP	8 x100 G	8 x400 G
Network processor (NP)	8 x 100 G	8 x 400 G
ODU-cross-connect (ODU-XC)	8 x100 G	8 x400 G

Fig. 6. (a) Architecture of a synthetic photonic node, (b) photonic network processor (P-NP) consisting of pools of DSPs, NPs, and ODU-XCs/L2-SWs, connected with reconfigurable optical interconnect, and (c) projected stages of the optical interconnect.

fully exploit emerging optical transmission technologies as well as future layer-2 functionality or higher-layer node functions. This photonic node can be seen as an extended version of a packet-optical transport node, but it has unlimited scalability and full flexibility. These characteristics allow it to define all the node features from transponder capabilities to higher-layer node functions by software and to incorporate the technologies of scale-free photonics and smart photonic networking.

The architecture of a synthetic photonic node is shown in Fig. 6(a). It consists of an optical cross-connect and a P-NP. The optical cross-connect of this node has all the features of the colorless, direction-less, contention-less cross-connect, as well as new capabilities. For example, it is grid-less (CDCG) thus enabling it to handle flexible WDM grids and is capable of SDM switching, which allows it to handle multi-core fibers or multi-mode transmission.

A P-NP will be a key building block as regards "smartness," namely capacity to synthesize desirable functions for switching nodes or OTPs by software. As shown in Fig. 6(b), it consists of pools of LSI chips of DSP for digital coherent signal processing, network processors or central processing units (NP/CPU),

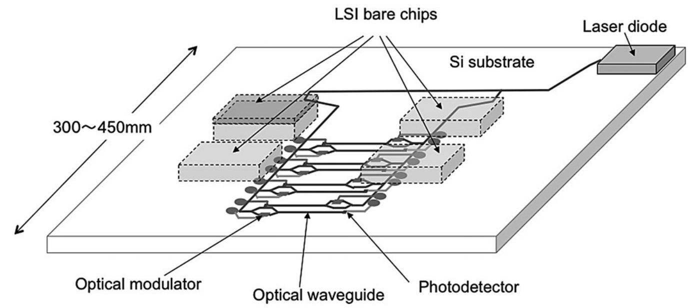


Fig. 7. Conceptual schematic of silicon optical interposer integrated with LSI bare chips. A laser diode, arrays of eight optical modulators and eight photodetectors are integrated on a silicon substrate. LSI bare chips are mounted on the interposer, and are electrically connected to the optical modulators and photodetectors.

and optical front-ends (O-FE), all connected by reconfigurable optical interconnections. The O-FE consists of a transmitter, a receiver, and a wavelength multiplexer/demultiplexer. By combining O-FEs and DSPs, we can configure any kinds of digital coherent optical transceivers for ultra-broadband channels based on various modulation formats. Such multiple-DSP modules will provide the computation power required to compensate for undesired interference between neighboring DWDM channels, caused by the cross-phase modulation resulting from fiber nonlinearity as well as linear inter-channel crosstalk, and multi-core operation requires the interconnection of DSPs. The NP/CPUs interface with an L2 switch from the clients and perform packet processing for layer-2 protocols or higher layer functions. They also work as the control plane for the photonic node. The switch fabric of ODU-XC/L2-SWs operates as the cross-connect of optical channel data units (ODU-XC) or packet-based logical channels.

As shown in Fig. 6(b) all the pools of devices are interconnected through reconfigurable optical interconnections. Therefore, any desired functional module can be configured by programming the optical interconnection pattern that connects a certain set of components from the pools of devices. The photonic network operation system manages all the resources of these device pools and controls their configuration. The P-NP always ensures the minimum power consumption because only the necessary components in the pool are activated. Moreover, it is fault-tolerant against component failure because it has a self-organizing capability for replacing a defective chip with a spare one in its pool.

To realize optical interconnections for the P-NP, it will be preferable to adopt a silicon optical interposer [35], [36]. A conceptual schematic of silicon optical interposer integrated with LSI bare chips is illustrated in Fig. 7. A laser diode, arrays of optical modulators and photodetectors, optical splitter, and waveguides are integrated on a silicon substrate. LSI bare chips are mounted on the interposer and are electrically connected to the optical modulators and photodetectors. The cw output from a laser diode is distributed to the optical modulator array through the optical splitter. The electrical signal from the LSI chip is detected with the photodetector and converted into optical signal by using the optical modulator, and it's sent to the other LSI chip, followed by the optical-to-electrical conversion. The LSI bare chips of the DSP, NP/CPU, and ODU-XC/L2-SW will be interconnected optically on the silicon optical interposer, while very short electrical wiring will be used for the interconnections between the neighboring O-FEs and the DSPs. This will be a key technology to reduce the power consumption and footprint as well as the cost because of its CMOS-compatible process, and thus creates a new value in the reduction of cost, the power consumption, and the footprint. The silicon optical interposer is projected to become available after 2020 [34].

By taking account of currently available 13" (300 mm) silicon wafer or 18" (450 mm) silicon wafer, which will be available in 2020, we can consider two target products of P-NP in the first and second stages as summarized in Fig. 6(c). As the area of a bare die will be 100 $\sim$ 200 mm^2, a few tens of bare DSP, NP/CPU, and ODU-XC/L2-SW chips can be integrated on a single silicon optical interposer. In the first stage, a total throughput of 800 Gb/s is projected, which could be deployed in a 100 Gb/s WDM link. In the second stage, the projected total throughput is 3.2 Tb/s, which might be deployed in a 400 Gb/s WDM link. Optoelectronic components in the O-FE and the OE and EO devices for the optical interconnect and hard-wiring will separately integrated, and they are assembled on the interposer by flip-chip bonding. In the first stage, a 25-Gb/s four-lane optical interconnect without WDM will be a better option because a colorless transmitter and receiver can be used. If a 4-wavelength $\times$ 25-Gb/s WDM becomes available for the optical interconnect, the interconnection footprint can be reduced. Challenges remain in terms of realizing the reconfigurability of the optical interconnect. In this respect there will be two options as regards the optical switch fabric, namely a space switch and wavelength routing.

IV. Use Cases of Photonic Network Processor

A. Use Case 1: Multi-Functional Optical Cross-Connect

One of the applications of the P-NP will be as a multi-functional colorless, directionless, contentionless, gridless optical cross-connect (CDCG-OXC). A CDCG-OXC must be able to accommodate a variety of client signals such as Ethernet (L2) packets, ODU frames, and the mixture of the two. When the type of client node or the traffic pattern changes, the CDCG-OXC must be able to respond by modifying its function. As shown in Fig. 8(a) there will be variations in the architecture, depending on the required functionality. The architecture at the top is suitable for transmitting L2 packets without ODU channel hierarchy. The pool of NPs at the top is configured for L2 protocol processors. The pool of ODU-XCs in the middle multiplexes or demultiplexes the client data traffic in ODU channel level. The architecture at the bottom is fully equipped with both pools of NP and ODU-XC, and can terminate L2 protocols of client data signals and multiplex/demultiplex them into ODU channels.

B. Use Case 2: Bit Rate-Flexible Optical Transponder

Let us consider two scenarios for upgrading transmission links from existing 100 Gb/s links. The options are either to add fixed-rate 100 Gb/s OTP or to replace 100 Gb/s OTPs with bit

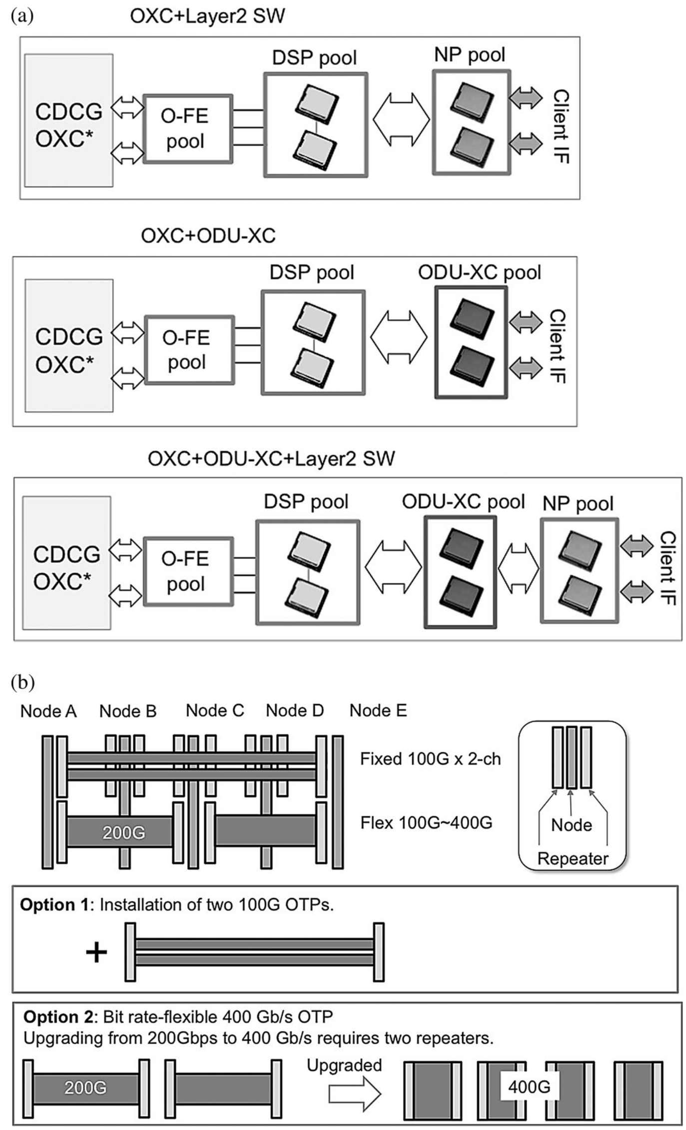


Fig. 8. (a) Use case 1: Multi-functional CDCG-OXC; with layer 2 switch, ODU-XC, and ODU-XC and layer 2 switch. (b) Use case 2: Upgrading scenarios of optical transponder (OTP): conventional bit rate-fixed OTP vs. bit rate-flexible OTP.

rate-flexible OTPs at the maximum bit rate of 400 Gb/s, whose bit rate can be remotely modified by software. A bit rate-flexible OTP is realized by changing the modulation format and/or the number of optical carriers [15]. Assume that a 200 Gb/s link is currently established between Nodes A and E as shown in Fig. 8(b), and there is a request from the customer for another 200 Gb/s between Nodes A and E.

1) Option I—Fixed 100 Gb/s OTP: We will simply add two 100 Gb/s OTPs, and the requested total link capacity is increased to 400 Gbps.

2) Option II—Bit rate-flexible 400 Gb/s OTP: We redefine the bit rate from the current 200 Gb/s to the requested 400 Gb/s by software update. For simplicity, we assume that the reach of 100 Gb/s is double that of 200 Gb/s, and 200 Gb/s is also double the reach of 400 Gb/s. Option I requires labor costs and time for the delivery. On the other hand, Option II needs repeaters but there is no need for any additional installation work because bit rate-flexible OTPs in Nodes B, C, and D are configured as 400 Gb/s remotely, and hence we can save both time and labor costs. Option II is future-proof, and it has an edge over Option I as regards service delivery time, and OPEX is lower because there are no labor costs.

V. Concluding Remarks

A photonic network vision for 2020 has been presented that envisions a "SPC." Photonic L2 virtualization has been discussed, which differs from the conventional approach in terms of the large number of slices and the large dynamic range of the bandwidth of each slice. Three key enabling technologies, namely scale-free photonics, smart photonic networking, and a synthetic transport platform, have been proposed. The P-NP is a key engine for realizing the above three enabling technologies that can synthesize multi-functional switches and transmission systems. Although there remains much to be studied how to realize the P-NP, silicon photonics could be one of the killer technologies. The P-NP, as a key building block, could pave the way to realize *White Box*-oriented transport equipment. Finally, a multi-functional optical node and a bit rate-flexible OTP have been presented as use cases of P-NP.

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