Abstract—A vision of photonic network in 2020 is presented, which envisages “smart photonic cloud” in the Big Data era. The smart photonic cloud is referred to as an atmosphere which serves as a universal infrastructure, providing with connectivities to machine-to-machine communications such as networked high-performance computing and intra- and inter data center networks. To cope with strong demands for network virtualization without any physical and logical constraint, its photonic layer 2 virtualization will becomes feasible, which differentiates from the conventional one in terms of the number of slices and the dynamic range of the bandwidth of each slice. For the starter, the guiding principle and the objectives of the vision will be addressed. Next, three “Ss” key enabling technologies, including smart photonic networking, synthetic transport platform, and scale-free photonics will be presented. A key building block to the above three enabling technologies is the photonic network processor, which can synthesize desired functions of the switch node and the transmission link. The photonic network processor leverages on a recent progress of digital signal processing for coherent optical transmission systems and an optical interconnect based upon silicon photonics, and it allows software-defining its functions.

Keywords—photonic network, optical fiber communications, network virtualization, digital signal processing

I. INTRODUCTION

Photonic network will play a crucial role in the coming Big Data era. Commerce, medicare, education, entertainment, and social life will more heavily rely on cloud computing in the near future. Data are generated from various sources such as sensor networks, scientific simulations of meteorology, genomics, and computational physics, financial transactions, social network services, Internet log of search engine etc. The collection of data sets, so-called Big Data, will be stored in the data centers (DCs), acting like a black body. According to the Cisco white paper, data center 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, one can mine the valuable information from data like extracting rare metals from used appliances. The analysis of Big Data, based upon real-time complex event processing (CEP), will be performed by exchanging huge data via inter-DC and intra-DC [2]. The size of data sets that are feasible to process in a reasonable amount of time is often limited by not only the processing capability but also by the bandwidth and the latency of data transfer over the networks.
Therefore, abundant bandwidth with low latency would be requisites for the network.

There is an interest example of the sensor network. The vending machine selling soft drink is going to be networked and equipped with an eye-tracking device of the customer, standing in front of the machine. The first eye contact of the customer at the display will provide the most important information. You want to collect this information from all the vending machines and analyze it online for improving the inventory control and efficiency of the logistics.

Another driver of the data traffic increase will be mobile phones. According to the 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 exa-bytes per month by 2017, 13-fold increase over 2012 at a CAGR of 66 \%. The data rate of mobile access has increased by 1600 times over 15 years since 1995. In 2017 the peak rate of mobile phone will reach 1Gbps by introducing LTE-advanced. The peak bit rate of mobile phone has been catching up the wireline access within 7 years, and the trend will be kept in the future. Since the mobile traffic are eventually backhauled by the photonic networks, and therefore the impact of rapid traffic growth of mobile phone on the core network would become more significant in coming years.

For the network operators, the cost reduction is imminent to be profitable under a strict price cap of the services, while they are solving a problem of capacity crunch due to the ever-increasing data traffic in the Big Data era. The reduction of operational capital expenditure (OPEX) remains to be tackled. Current network operation and management is labor-intensive. For example, if there is need for upgrading the transmission capacity of a link, workers are sent to the sites to exchange the module or card of the optical transponders. It will take the labor cost and several hours or more, excluding several weeks for preparing additional modules. The setup of optical paths is currently conducted manually by changing the connections of cross-connect on site, and hence it also takes labor cost and a long time. If the optical transponder can be automatically upgraded by being software-defined from a remote site, and if the switch can be automatically configured, the OPEX can be saved, and the time for service delivery can be minimized. A solution path to reduce the OPEX would make the photonic network less labor-intensive. A key to the solution would be “smartness,” the capability of synthesizing desired functions of the switching and transmission by the software control.

In this paper, a vision of photonic network in 2020 is presented, which envisages “smart photonic cloud (SPC)” in the Big Data era. The SPC is referred to as “Atmosphere” which serves as a universal communication infrastructure, providing with connectivity to machine-to-machine communications such as networked high-performance computing and storage and intra- and inter DC networks. To cope with strong demands for network virtualization without any physical and logical constraint, its photonic layer 2 (L2) virtualization will be studied, which can differentiate from the conventional one in terms of the number of slices and the dynamic range of the bandwidth of each slice. For the starter, the guiding principle and the objectives of the vision will be addressed. Next, three “Ss” key enabling technologies, including smart photonic networking, synthetic transport platform, and scale-free photonics will be presented. A key building block to the above three enabling technologies is the photonic network processor (NP), which can synthesize desired functions of the switch node and the transponder. The photonic NP leverages on the recent progress of digital signal processing for equalizing signal impairments in digital coherent optical transmission systems and an integrated optical interconnect based upon silicon photonics along with the capability of software-defining its functions.

II. GUIDING PRINCIPLE AND ITS OBJECTIVES TO SMART PHOTONIC CLOUD (SPC)

A. Current Status of Photonic Network

Current photonic network is opaque, and the network configuration is static. More precisely, reconfigurable optical add/drop multiplexer (ROADM) has been deployed in metro ring network, but the core network uses electronic switches at the nodes. The deployment of long-haul 100Gbps dual-polarization quadrature phase-shift keying (DP-QPSK) digital coherent transmission system [4] is underway. It will still take time for a large port count optical cross-connect to be deployed in the core network. The total capacity per fiber is limited to several tera-bps with fixed WDM grid. The energy-efficiency is poor due to large power consumption of routers in the architecture of IP over WDM network.

As shown in Fig.1, by 2015 the R&D challenges for larger transmission capacity and better spectral efficiency will be completed. The target bit rate per single channel will range from 400Gbps to 1Tbps. Ultra-DWDM such as superchannel or Nyquist WDM [5] will be the key technology to improve the spectral efficiency, targeting the total transmission capacity of several tens to a hundred tera-bps per single core. Flexible WDM grid based upon elastic bandwidth assignment...
of the channel [6] will be introduced by installing bandwidth-variable wavelength selective switch (WSS) at the nodes. The management of spectral resource will evolve from the conventional fixed grid assignment to flexible one. But potential of photonics and optics has not yet been fully exploited in photonic networks.

B. Guiding Principle

Photonic network vision 2020 envisages the SPC in Big Data era after 2020. The SPC is “Atmosphere” which serves as a universal communication infrastructure without any physical and logical constraint, providing with connectivity to machine-to-machine communications such as the exascale computing, networking, storage and analysis [7] and intra- and inter DC networks. The SPC is just like constraint free version of the Internet of Things (IoT) that provides everything with the Internet connectivity and everything can communicate via the Internet. To realize the SPC, the R&D issues to be tackled for the five years in the period of 2016-2020 are addressed. The target photonic network must be value-creative for users by providing opportunities to create innovative networked applications, and for the operator it must drastically reduce the CAPEX/OPEX. In order to fulfill the above-mentioned goals, Layer 2 (L2) must be evolved to “Photonic L2.” In the photonic L2 the optical processing capability is explored where it performs better than the electronic counterpart, thus eliminating bottlenecks in the speed and bandwidth that conventional L2 technology has.

C. Objectives

Toward the goal of SPC, the objectives are threefold.

Objective 1: Value-creative network

To make the photonic network to be value-creative for the customers by giving opportunities of creating a wide variety of networked applications, the photonic network has to be smart so as to be virtualized to any customers’ needs. The SPC provides photonic L2 slices, and each of the slices acts like a single switching hub, providing the customers with simple end-to-end connectivity with the minimum latency. Also, it should be easy to access like plugging one’s electrical power socket. At the same time, the network operators have to be benefitted from the capability of software-defining desired functions of switch node and transponders, leading to a drastic reduction of their OPEX.

Objective 2: Evolution of Layer 2 to Photonic Layer 2

Wide area L2 switching network should replace hop-by-hop IP routing, in order to mitigate bottlenecks of the poor energy-efficiency and large latency. The photonic L2 network should evolve from conventional L2 network by exploiting inherent nature of photonics and optics such as its high-speed, abundant bandwidth, and massive parallelism in the all-optical processing capability. It will provide an end-to-end connection with ultimately low latency as close as to the propagation delay.

Objective 3: Key driver for innovations

Photonic NP must be a key building block of “smartness,” the capability of synthesizing desirable functions of the switch node and transponder by the software control. It leverages on recent progress of digital signal processing for equalization of the signal impairments in digital coherent optical transmission systems and integrated optical interconnect based upon Si-photonics. One can synthesize on-demand functions of transponders or switches using the photonic NP, which will be detailed in III. B.

III. THREE “SS” KEY ENABLING TECHNOLOGIES

Three “Ss” key enabling technologies starting from alphabet S, including smart photonic networking, synthetic transport platform, and scale-free photonics will be discussed, which serve as the bases of creating the SPC.

A. Smart Photonic Networking

The role of the photonic L2 is in the data link layer, consisting of three sub-layers of L2 PHY, MAC Bridge, and MAC Edge from the bottom. The smart photonic network does not intend to emulate conventional Ethernet protocol as it stands, but it intends to create photonic-native data transport protocol, which will be much simplified from Ethernet.

The photonic L2 PHY offers a number of transparent links with flexible bandwidth up to one tera-bps on flexible frequency grids, established on either single core or multi-core fiber. To leverage on the abundant bandwidth and the minimum latency of photonic L2 PHY, the MAC Bridge performs either bypassing data on the wavelength path or switching by using either switching of the time slot, packet, or space. In the MAC Bridge sub-layer, all-optical processing will be eventually adopted and combined with the digital electronics in such a way that the best of both powers can be fully exploited. On the other hand, the other processing of the Ethernet protocol such as farming, link adaptation, and the operation and management (OAM) are left to the MAC Edge, which are performed in electronic domain.

Virtualization using photonic L2 slice makes it different

![Fig.2 Capacity per slice as a function of the number of slices for conventional virtualization using electrical path and wavelength path. Photonic L2 virtualization can fill the vacancy of conventional ones.](image-url)
from conventional one. Each of the slices acts like a single switching hub, providing the users with simple end-to-end connectivity with low latency. Figure 2 plots the capacity per slice as a function of the number of slices. Currently, the network virtualization is exclusively done by using electrical paths e.g., Ethernet virtual local area networks (VLANs). The slice in electronic domain can provide a large number of slices, e.g., 10 thousands but the capacity of each slice will be limited. Scaling the number of slices will be prohibitive due to the large power consumption as well as a large control overhead.

On the other hand, the number of the optical path-based slice in WDM network is limited up to 100. What differentiates photonic L2 virtualization from the above legacy ones are the followings. First, it can scale out the number of the optical path-based slices in WDM network, owing to the capability of handling sub-wavelength and the flexible spectral arrangement. Second, a large dynamic range of slice capacity of around 30 dB ranging from 1Gb/s to 1 Tbit/s will be provided by utilizing adaptive modulation format and/or multi-carrier modulation format. Note that the number of virtualized networks of photonic L2 would become comparable to the one of VLANs, 4096 in the case with 12 bit tags and 16.8 millions with 24 bit tags. Therefore, the photonic L2 virtualization can fill the vacancy in the chart of Fig.2 where neither the electrical slice nor the optical path based slice can fill.

B. Synthetic Transport Platform

It is foreseen that digital coherent transmission will prevail not only in log-haul transmission links but it will also be introduced in the metro area and access networks in 2020. The digital signal processor (DSP) performs equalization of an optical signal after the transmission by compensating the impairments due to the chromatic and polarization dispersions as well as nonlinear effects. The DSP can also be used as the pre-compensation of the signal impairments before the transmission.

In the photonic NP in Fig.3 (a), there are pools of DSP module, NP module, switch fabric, optical front-end (FE) including transmitter, receiver, forward error correction (FEC) processor, framer, and mapper. On top of the photonic NP in Fig.3, there is the photonic network operation system (NW-OS). The photonic NW-OS allows the software to synthesize desired function by controlling the pools of devices. As the open innovation prompts an efficient and quick R&D, the photonic NW-OS should be opened to any vendors for the rapid innovation. There is a successful example of OpenFlow, which has been promoted by Open Network Foundation (OFN) [8].

A desired function can be configured by optically interconnecting the components from the pools of the devices and components. The photonic NP will always ensure the minimum power consumption because only the necessary components in the pool are interconnected and activated, but the unnecessary components are disconnected without power supply. In Fig.3 (b) the module examples of DSP core and NP core and the user-network interface (UNI) are illustrated. By using these modules, for example, the optical transponder and switch node can be constructed.

The photonic NP will adopt photonic integrated circuit (PIC) technology [9]. Hybrid integration capability of various photonic devices together with optical interconnects will play a crucial role. Particularly, Silicon photonic looks promising due to its compatibility with CMOS process of ICs [10]. By 2020 optical interconnect technology will be developed for the multi-core processor on a silicon wafer. A challenge will be the integration of optical switches and wavelength multiplexer and demultiplexer, in order to make the optical interconnect reconfigurable. The footprint of conventional wavelength multiplexer and demultiplexer such as an arrayed waveguide grating is too large for the integration with CMOS, and it’s an open question how the novel compact scheme is implemented.

The functions of switch node and the transponder can be synthesized on demand. A synthetic photonic node having the wavelength selective switch (WSS) and space switch is constructed with the photonic network processors as shown in Fig.4. The proposed node enables to software-definitively provide the necessary functions of node according to required capacity per slice. The incoming signals to the intermediate
node are wavelength-demultiplexed and experience the OEO conversion at the transponder, and its signal impairments are restored by the DSP. A concept of digital ROADM has been proposed which adopts the OEO conversion and add/drop the traffic by the electronic switch [11], but the equalization of signal using DSP has not been out of the scope. The bypass traffic which does not need the restoration of signal impairment will transparently pass through the node. The add/drop traffic to be terminated at the site is switched to an appropriate drop port. The switching could be performed either optically or electronically. An optical cross-connect switches the optical paths after OEO conversion, while packets will be forwarded through electronic switch before the EO conversion.

C. Scale-free Photonics

The terminology of “scale-free” is referred to the elimination of physical limitations, e.g., to the port count and switching speed of switch fabrics and non-repeater transmission distance. Here, two targets are focused on, optical transmission and switch fabric. Digital coherent transmissions system will dominate beyond 100Gbps, and it will be eventually deployed in metro-access network if a few years. The low noise figure (NF) of the in-line optical amplifier has a big impact on the long-haul transmission systems in terms of the system cost as well as the power consumption. If the in-line optical phase-sensitive amplifier (PSA) is adopted in a long-haul transmission link as shown in Fig.5, a drastic extension of non-repeater span is expected, resulting in the power saving consumed by the amplifiers. Toward 2020 and beyond, the development of an ultimately low NF in-line optical amplifier will be a challenge. The theoretical NF of an ideal optical PSA is 0 dB [12]. Recently, PSA has been gaining attention and demonstrating low noise characteristics and waveform shaping effect for PSK and quadrature amplitude modulation (QAM) signals [13,14]. The PSA heightens signal-to-noise ratio (SNR), eventually the multi-level of QAM and PSK modulation formats would go higher.

No-guard band Nyquist WDM transmission system will preferably adopt the digital coherent technique, it might be useful to deliver references of optical frequency and phase to the transmitters and receivers at remote sites through frequency and phase synchronous network on a global scale and calibrate the light source and local oscillator on site. A highly stabilized optical frequency comb generator and optical phase-locked loop will be promising for the calibration [15,16]. The target uncertainty of the optical frequency will be ±1 MHz in 2020.

The ultimate throughput and versatile data granularity in switching has to be challenged in the domains of time/frequency/space. The challenges include a flexible WSS for no-guard band Nyquist WDM and orthogonal code-division-multiple access (OFDM) and multi-degree ROADM either for space division multiplexing (SDM) using a multicore fiber or mode division multiplexing (MDM) using a multimode fiber.

IV. CONCLUDING REMARKS

The photonic network vision in 2020 has been presented, which envisions “smart photonic cloud (SPC)” in the Big Data era. The photonic layer 2 (L2) virtualization has been discussed, which differentiates from the conventional one in terms of the large number of slices and the large dynamic range of the bandwidth of each slice. Three key enabling technologies, including smart photonic networking, synthetic transport platform, and scale-free photonics have been discussed. The photonic network processor (NP) has been proposed as a key building block to the above three enabling technologies, which can synthesize desired functions of the switch node and the transmission link. The photonic NP leverages on a recent progress of DSP for digital coherent optical transmission systems along with optical interconnect technology based upon silicon photonics. Some of the use cases of the photonic NP will be presented on site.

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